

CLOUD AND SYNOPTIC PARAMETERS  
ASSOCIATED WITH CLEAR AIR TURBULENCE

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## ABSTRACT

The research was initiated to determine relationships between clear air turbulence (CAT) in the stratosphere and upper troposphere, and meteorological variables, circulation features and cloud characteristics. For this purpose, a total of 372 cases of CAT occurrence and non-occurrence were analyzed using aircraft instrumented reports of CAT in the 45,000—70,000 ft layer as obtained by the U.S. Air Force in Project HICAT from 1966 through 1968.

Light to moderate or more intense CAT occurs frequently when the vertical temperature profile about the level of interest is irregular and includes both strong inversions (locally large values of vertical wind shear) and layers in which the temperature decreases rapidly with height (a region of decreased thermal stability within a generally stable stratosphere). Consistent numerical relationships were determined for a number of meteorological variables describing this condition. Implementation of these results for the development of CAT detection instrumentation is discussed.

The analysis of circulation features showed that significant stratospheric CAT was associated with large horizontal temperature gradients at upper-level surfaces. Cloud characteristics associated with significant turbulence were cirrus bands and streaks, a well-defined frontal cloud band, transverse wave clouds, and cumulonimbus clouds.

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Dr. Duane Cooley was Co-Principal Investigator during the first year of this two-year effort. He made many significant contributions and, in particular, devised the initial procedure for analyzing satellite pictures using HICAT data (Phase 2).

Several individuals at The Center for the Environment and Man, Inc. and its predecessor, The Travelers Research Corporation, also contributed. Mr. Charles Mulé efficiently accomplished a variety of data preparation and analysis tasks and made helpful suggestions to expedite this work. Mr. Frank Perry with the guidance of Dr. Marshall Atwater wrote the program to compute meteorological variables from radiosonde and rawinsonde measurements.

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## 1. INTRODUCTION

The objectives of the research described in this report are to study cloud and synoptic parameters associated with clear air turbulence (CAT) in the stratosphere and upper troposphere, to determine relationships between CAT and these parameters, and to develop a model or set of procedures for the prediction of turbulence occurrence. The research is specifically directed toward the ultimate delineation of those atmospheric parameters most associated with CAT occurrence for subsequent design of detection instrumentation.

Turbulence in the atmosphere, in general, refers to the instantaneous departure of the wind flow from a time-averaged mean. In CAT research, we are specifically concerned with those fluctuations or "eddies" in the wind flow that have a scale dimension (approximately 70—700 feet) to which current aircraft are responsive. Aircraft response is felt as a series of vertical accelerations or "bumps" that cannot ordinarily be compensated for by the pilot. CAT in the upper troposphere and lower stratosphere includes turbulence encountered by aircraft both in clear air (clouds may be present below or above the aircraft level) and in or close to cirrus clouds. Thunderstorms and large updrafts encountered in and very near convective clouds are considered a separate problem.

### Background

A detailed discussion of previous CAT research and currently projected programs are outlined in reports by Pao and Goldberg [1], and Dutton [2], and in the Federal Plan for Clear Air Turbulence [3]. As background for evaluation of the results of this study, a condensed summary of previous studies follows.

Clodman, Morgan and Ball [4] proposed two basic mechanisms associated with 1.) the presence of gravity waves and strong vertical wind shear, and 2.) dynamic instability (strong anticyclonic wind shear and curvature) and low Richardson Number. Reiter and Nania [5] indicate the occurrence of clear air turbulence in thermally stable layers of the atmosphere in which the wind is turning with height and also suggest a gravity-wave mechanism. In relatively thin layers in which the vertical wind shear is strong, the large scale wind flow can become disorganized, resulting in the transfer of energy to higher wave numbers and into small scale turbulence [6].

Numerous studies during the 1950's and 1960's have associated turbulence in the mid- and upper troposphere with synoptic features such as upper-level troughs and lows, the jet-stream and tropopause and upper level fronts and thermal ribbons [7]. The variance of results is not surprising considering the differing characteristics of the data samples. Some meteorological variables that are related to turbulence occurrence are: wind speed, vertical and horizontal wind shear, temperature lapse rate, horizontal temperature gradient, differential temperature advection, Richardson Number, and derived quantities such as the divergence and vorticity of the wind, and the product of wind speed, and turning of the wind with height [8].

It should be noted that all synoptic studies reflect indirect statistical relationships since turbulence which is a micro-scale phenomenon is being related to atmospheric flow and stability which are observed on a synoptic scale (100 to 1000 mi). When subjective (non-instrumented) reports of turbulence constitute the sample being analyzed, the difficulties in establishing strong relationships are obvious.

Some stratospheric CAT sampling programs suggest that CAT tends to decrease in both frequency and intensity above 40,000 feet altitude. However, moderate to severe turbulence has been experienced at altitudes up to 70,000 feet by U-2, Canberra, B-70 and SR71 aircraft [9]. Analyses of HICAT data by Crooks, et al. [10] reveal that the median dimensions of stratospheric CAT areas below 70,000 feet seem to be of the order of 15 miles in the horizontal and 2000 feet in the vertical. The dimensions of turbulence patches in the troposphere are similar in vertical extent but have average horizontal dimensions of about 50 miles [11]. In all discussions of changes in turbulence characteristics with altitude, one must be aware of the differences in type (subjective or instrumented), quality, and quantity of input turbulence data. Furthermore, considerations must be given also to such factors as location, season, time of day and any temporal and spatial differences existing among different types of data.

Utilizing CAT data obtained with an XB-70 airplane [12], Ehernberger [13] concluded that several parameters are required to specify CAT occurrence because of the variety of atmospheric conditions under which it may be experienced. Kadlec [14] noted from evaluation of data from 13 XB-70 flights that CAT is more clearly related to temperature inversions in the stratosphere than in the troposphere. In an analysis of Project HICAT U-2 flights, Waco [15] determined that low Richardson Number



and large values of the minimum vertical potential temperature gradient were frequently present with CAT. Ashburn, et al. [16], also showed that both the intensity and frequency of CAT decreased above 55,000 feet altitude over low relief terrain; this was not true over mountains.

#### Satellite Research

Satellite pictures depict cloud features associated with both synoptic-scale and meso-scale circulation features. The principal cloud features are: size, shape and organization, orientation, texture, tone or brightness, presence of shadow and overall homogeneity. As an example, Viezee, et al. [17] studied four features of jet-stream cirrus clouds (shadow lines, sharp-edged cirrus sheets, cirrus bands and transverse waves) in relation to the observed wind field. Crooks, et al. [10] noted from aircraft cloud photographs that turbulence was found to occur above an abrupt edge or a large break in the cirrus deck, high lenticular cirrus clouds, the tops of cumulonimbus clouds and cirrus streaks or wisps and long streaming cumulonimbus anvils. In our investigation satellite video data were studied to acquire information regarding both synoptic and meso-scale circulation features related to CAT occurrence. We are concerned with determining the importance of upward propagations from upper tropospheric levels as revealed by these video data.

The ALLCAT program [18] in general and, specifically, the HICAT flight data presented an opportunity to examine a significant volume of instrument turbulence measurements from the stratosphere which permit an examination and assessment of the applicability of extending tropospheric turbulence theory to the stratosphere. In addition to these HICAT data, other data utilized in this study include satellite video data, commercial aircraft reports of turbulence, meteorological vertical soundings of temperature and winds, and constant-pressure surface analyses.

The primary source of turbulence data was obtained in Phases 2 and 3 of the Project HICAT program. From these data a total of 372 cases of turbulence occurrence and non-occurrence were defined. The results obtained from the analyses of the Phase 2 sample together with a study of tropospheric CAT were reported in an interim report [19] at the conclusion of the first year of study. In the second year, the Phase 3 sample was analyzed and results were compared with and combined with those obtained

from the Phase 2 samples. This procedure was followed with respect to all of the parameters studied—meteorological variables, circulation features and cloud characteristics—that permitted a realistic assessment of their relative value for delineating regions of CAT occurrence. Particular emphasis was placed on evaluating the statistical stability of the results, that is, the numerical consistency or lack of consistency in discriminating among defined categories of CAT when comparing the two samples.

The data analyzed in the 2-year study are described in Section 2. The detailed technical analyses of data are presented in Section 3. A procedure for locating probable CAT regions in the stratosphere is discussed in Section 4. Finally, Section 5 presents recommendations for further CAT research based on the results of this study and anticipated operational aircraft requirements.

## 2. DATA SOURCES

The principal source of turbulence data was instrumented reports of CAT in the stratosphere collected by the U.S. Air Force in the HICAT (High Altitude Clear Air Turbulence) portion of their ALLCAT program [20]. These data are published in three volumes [10] containing flights between October 1965 and February 1967 (Phase 2) and in two volumes [21] for the period March 1967 through February 1968 (Phase 3). These reports include flight descriptions and flight track maps, total hours flown and time flown in CAT, horizontal and vertical locations with measurements of intensity of turbulence regions, and radiosonde data from 150 mb to 50-mb constant pressure surfaces including significant temperature levels (Phase 2 only). For portions of most flights, gust velocity time histories and power spectra of vertical, longitudinal and lateral gust velocities are included. The flight data were collected at altitudes from 45,000 to 70,000 feet over various locations in and near the contiguous United States, Hawaii, Alaska, Australia, New Zealand, England and Panama. In the Phase 2 program, 29.2 hours of CAT were encountered over flights covering 256,000 miles (649.5 flight hours). In the Phase 3 portion, 18.3 hours of CAT were recorded over 156,000 miles (477.6 flight hours). In the original editing of the data, the intensity of CAT was classified according to the estimated level of the center of gravity (cg) acceleration peaks as follows [10]:

<u>CAT category</u>	<u>Frequently occurring peak g increment</u>
Very light (VL)	$\pm 0.05$ to $\pm 0.10$
Light (L)	$\pm 0.10$ to $\pm 0.25$
Moderate (M)	$\pm 0.25$ to $\pm 0.50$
Severe (S)	$\pm 0.50$ to $\pm 0.75$
Extreme (X)	$\pm 0.75$ or greater

Other intensity classifications used are light to moderate (LM) and moderate to severe (MS). Occasional cg accelerations of  $\pm 0.25$  to  $\pm 0.50$  result in an LM classification and similarly, occasional peaks of  $\pm 0.50$  to  $\pm 0.75$  dictate a MS classification. Subjective pilot reports were utilized in this study to define cases of more intense CAT ( $\geq$  LM) in a few instances and were primarily employed to corroborate that no turbulence or only very light or light CAT were encountered.

Phases 2 and 3 HICAT data constitute the basic turbulence data used in this study. Table 2-1 lists the dates of cases analyzed from the HICAT sample. Other information included in the table is the location, total number of cases, number of cases of light-to-moderate or greater CAT and whether satellite video coverage was included. Data from the flights over England, Australia and New Zealand were not included. Only limited use was made of the flight data over Alaska because background illumination in February 1967 precluded obtaining useful ESSA 2 pictures. Nearly all other cases of light-to-moderate or more intense CAT measured in the HICAT program were included regardless of the quality of the satellite picture data.

A second source of data was a compilation of collected military and commercial subjective pilot reports of CAT primarily in the 30,000- to 40,000-foot layer for the period January-June 1966. These include time, location, altitude, estimate of intensity, type of aircraft and occasionally temperature and wind data. This sample does not contain reports of non-occurrences of CAT or of CAT with a subjective intensity of less than light to moderate. By definition, an individual case of CAT consisted of the most representative intensity of at least 3 to 5 subjective reports. A total of 47 cases were selected with 22 characterized by light to moderate intensity, 22 as moderate, and 3 as moderate to severe CAT. Table 2-2 indicates the dates and number of cases.

Meteorological variables were computed from standard rawinsonde soundings taken twice daily at 0000 and 1200 GMT. For Phase 2 data, tabulations of wind direction and speed at mandatory constant pressure levels (150, 100, 70 and 50 mb) and temperatures at these levels and at significant levels were listed in Volume III of the Project HICAT publication [10]. These data were supplemented by height, temperature, and wind data at intervening standard pressure levels (125, 80 and 60 mb) which were extracted from Northern Hemisphere Data Tabulations on microfilm. Additionally, sounding data from 400 to 150 mb were tabulated. The required wind and temperature soundings for the Phase 3 sample were obtained from WBAN 31A & B forms supplied by the National Weather Records Center, ESSA and from Northern Hemisphere Data Tabulations.

Detailed and small-scale variations of the temperature and wind fields in the vertical are not available from the regular sounding data. This is particularly true

TABLE 2-1  
SELECTED HICAT CASES

PHASE 2				PHASE 3			
Date	Location	Instrumented measurements of light to moderate or greater CAT	Satellite photo coverage	Date	Location	Instrumented measurements of light to moderate or greater CAT	Satellite photo coverage
Nov 17, 1965	Western U.S.	yes	no	Mar 13, 1967	Western U.S.	yes	yes
Mar 22, 1966		no	yes	May 2, 1967	South Central U.S.	yes	yes
Mar 25, 1966		no	yes	May 3, 1967		yes	yes
Mar 28, 1966		no	yes	May 5, 1967		yes	yes
Mar 31, 1966		yes	yes	May 8, 1967		yes	yes
Apr 1, 1966		yes	yes	May 10, 1967		yes	yes
Apr 5, 1966		no	yes	May 12, 1967		yes	yes
Apr 6, 1966		no	yes	May 15, 1967		yes	yes
Apr 18, 1966	Pacific Ocean	no	yes	May 16, 1967		yes	yes
Apr 20, 1966		yes	no	May 17, 1967		yes	yes
Apr 21, 1966		no	yes	May 19, 1967		yes	yes
Apr 22, 1966		no	no	May 22, 1967		yes	yes
Apr 25, 1966		yes	no	May 25, 1967		no	yes
Apr 26, 1966		no	yes	Jun 20, 1967	North-east U.S.	no	yes
Apr 27, 1966		no	yes	Jun 29, 1967		no	yes
Apr 29, 1966		yes	no	Jun 30, 1967		no	yes
May 2, 1966		yes	no	Jun 5, 1967		yes	yes
May 5, 1966		no	yes	Jul 6, 1967		yes	yes
May 10, 1966		no	yes	Jul 7, 1967		no	yes
May 13, 1966		yes	yes	Jul 14, 1967		no	yes
May 16, 1966		yes	yes	Jul 27, 1967	Panama	yes	yes
May 17, 1966		no	no	Aug 2, 1967		yes	yes
May 19, 1966		yes	yes	Aug 4, 1967		yes	yes
May 20, 1966		yes	no	Aug 7, 1967		yes	yes
Aug 24, 1966	Western U.S.	no	yes	Sep 11, 1967	South-east U.S.	no	yes
Aug 29, 1966		yes	yes	Sep 12, 1967		no	yes
Aug 30, 1966		yes	no	Sep 19, 1967		no	yes
Aug 31, 1966		no	yes	Sep 20, 1967		no	yes
Sep 21, 1966	Eastern U.S.	yes	yes	Sep 21, 1967		yes	yes
Sep 28, 1966		no	yes	Sep 28, 1967		no	yes
Sep 29, 1966		no	yes	Sep 29, 1967		no	yes
Sep 30, 1966		yes	yes	Oct 2, 1967		no	yes
Oct 18, 1966		no	yes	Nov 16, 1967	Western U.S.	no	yes
Oct 20, 1966		yes	yes	Nov 17, 1967		yes	yes
Oct 21, 1966		no	yes	Nov 20, 1967		yes	yes
Oct 24, 1966		yes	yes	Nov 21, 1967		yes	yes
Oct 25, 1966		no	yes	Nov 28, 1967		no	no
Oct 26, 1966		no	yes	Nov 29, 1967		yes	yes
Oct 27, 1966		no	yes	Nov 30, 1967		yes	yes
Oct 28, 1966		yes	yes	Dec 1, 1967		yes	yes
Nov 4, 1966	Caribbean	yes	yes	Dec 2, 1967		yes	yes
Nov 7, 1966		yes	no	Jan 31, 1968	Western U.S.	no	yes
Nov 9, 1966		no	yes	Feb 1, 1968		no	yes
Nov 10, 1966		yes	yes	Feb 2, 1968		yes	yes
Nov 14, 1966		no	yes	Feb 8, 1968		no	yes
Nov 15, 1966		no	yes	Feb 14, 1968		no	yes
Nov 16, 1966		yes	yes	Feb 15, 1968		yes	yes
Nov 17, 1966		no	yes	Feb 16, 1968		yes	yes
Nov 21, 1966		no	yes	Feb 19, 1968		yes	yes
Nov 23, 1966		no	yes	Feb 26, 1968		no	yes
Jan 1, 1967	Western U.S.	yes	yes	Feb 28, 1968		no	yes
Jan 16, 1967	Alaska	yes	no				
Feb 6, 1967		yes	no				

Total cases: 176  
Total photo cases: 90  
Total cases of light to moderate or greater CAT: 40

Total cases: 196  
Total photo cases: 112  
Total cases of light to moderate or greater CAT: 38

TABLE 2-2  
SUBJECTIVE CASES OF LIGHT TO  
MODERATE OR MORE INTENSE CAT IN  
THE UNITED STATES

Date	No. of cases
Feb 11, 1966	3
Feb 12, 1966	3
Feb 15, 1966	5
Feb 16, 1966	2
Mar 17, 1966	5
Mar 18, 1966	3
Mar 22, 1966	5
Mar 31, 1966	1
Apr 2, 1966	1
Apr 3, 1966	3
Apr 18, 1966	1
Apr 19, 1966	4
Apr 25, 1966	2
Apr 25, 1966	2
May 10, 1966	2
May 11, 1966	2
May 16, 1966	2
May 20, 1966	1
Jun 9, 1966	1
Jun 19, 1966	1
Jun 10, 1966	1

of the wind field where radar data, like that obtained by the Jimsphere balloon, is required for the precise determination of vertical wind shear over a thin layer. However, with a sufficiently large sample, the regular sounding data can be effectively utilized. Perhaps the most important problem is the higher frequency of missing wind data in the stratosphere during conditions of strong wind flow and increased likelihood of significant (light to moderate or greater intensity) CAT.

Weather satellite pictures were acquired from ESSA 1, ESSA 2, ESSA 3 and ESSA 5. Pictures from the Automatic Picture Transmission cameras [22] aboard ESSA 2 were prepared in the form of mosaics on 20 x 24 in. photographic paper by the National Environmental Satellite Center (NESC) of ESSA. Individual pictures used in composing these mosaics were received on facsimile recorders. Pictures from the other satellites

were received on 35 mm microfilm from the National Weather Records Center (NWRC) of ESSA.

These satellite systems provide a best horizontal resolution of about two to three miles at the earth's surface. This is adequate to distinguish the general type of larger cloud masses (stratiform, cumuliform, or cirriform), but small cumulus and thin cirrus are frequently indistinguishable.

The circulation analyses used were those published by the Free University of Berlin [23, 24, 25, 26] for the surface and the 300-mb and 100-mb constant-pressure surfaces. The 300-mb level is representative of conditions in the upper troposphere at about 30,000-ft altitude. The 100-mb level is close to 53,000 ft and is representative of that portion of the stratosphere close to the levels of most of the HICAT flights (50,000—65,000 ft). These analyses are made over the entire Northern Hemisphere; they are characteristically smooth and depict large-scale circulation features. Analyses at the surface and the 500-mb level for the North American region, transmitted from the National Meteorological Center, were also utilized.

### 3. ANALYSIS AND RESULTS

From the basic HICAT Phase 2 and 3 data sample described in the previous section, 372 cases of turbulence and no turbulence were defined and associated with the closest radiosonde station. These cases were used in association with circulation features while a somewhat different procedure was required when analyzing the satellite data described in Section 3B.

Each case contained the following information:

- (1) flight track map of entire flight;
- (2) location on flight track of measured CAT "runs";
- (3) summary of pilot evaluation of CAT intensities and locations; and
- (4) distribution of radiosonde stations.

A few guidelines were:

- A portion of the flight track was considered non-turbulent if there were no processed turbulent "runs" and no indication of CAT by the pilot;
- Subjective reports of very light and light CAT by the pilot were accepted, if the information was precise, particularly with regard to location;
- Cases of light to moderate or more intense CAT were defined only from instrumented measurements of CAT except in three cases where particular circumstances warranted accepting the pilot report;
- Individual cases of CAT and no turbulence were required to be approximately 100 nautical miles apart or separated by at least 5000 ft in the vertical. There were only a few instances when more than one case of CAT was defined at the same location by satisfying the vertical separation requirement;
- When a series of turbulence runs were reported in one locality the intensity chosen for the case reflected the most intense CAT measured in any of the runs;
- For some flights, a best estimate of the probable flight altitude had to be made for individual cases. This estimate was obtained from recorded heights at locations of earlier or later turbulence runs and also from pilot comments;
- Each defined case was associated with the closest reporting radiosonde station and each available radiosonde sounding was associated with only one segment of



flight location. Since the flights were frequently planned to pass close to radiosonde station locations in only 41 of 372 cases did the separation exceed 100 nautical miles. In almost all cases the temporal separation was less than 6 hours and frequently was less than 3 hours.

### A. Meteorological Variables

A computer program was written to compute the values of the meteorological variables associated with clear air turbulence (CAT). Complete specifications which describe the program written for an IBM 360/40 computer are presented in our interim report [19].

The results in this section reflect the completion of the analysis of the relationships between the occurrence and non-occurrence of CAT and meteorological variables computed from temperature and wind sounding data for both Phase 2 and Phase 3 HICAT data. Where appropriate, a statistical testing of the relative strengths of the relationships was made.

#### Average Values for CAT Categories: Phases 2 and 3 Compared

Table 3-1 gives, for 13 variables, their average value for five categories of turbulence intensity computed from the Phase 3 data. The number of cases is given below:

<u>Category</u>	<u>Number of cases*</u>	
	<u>Phase 2</u>	<u>Phase 3</u>
O—no CAT	67	101
VL—very light CAT	26	15
L—light CAT	43	41
LM—light to moderate CAT	13	15
≥M—at least moderate CAT	27	23

\*Due to occasional missing data for total profile analysis, the precise number of cases on which the averages are based may in some instances vary slightly.

Since the number of cases in individual categories is not large, the "none and very light" categories were combined as were the "light to moderate" and "moderate or greater" categories. The averages computed for these combined categories are shown in Table 3-2 for both Phase 2 and 3 data samples.

TABLE 3-1  
AVERAGE VALUES OF METEOROLOGICAL VARIABLES FOR  
SEVERAL TURBULENCE INTENSITY CATEGORIES—PHASE 3 DATA

(Total Cases: 195)

Variables	Units	CAT Intensity				
		None	Very Light	Light	Light-Moderate	Moderate or Greater
$ \gamma $	$\frac{^{\circ}\text{C}}{100 \text{ ft}}$	0.07	0.09	0.08	0.10	0.11
$\gamma_{\text{max}}$	$\frac{^{\circ}\text{C}}{100 \text{ ft}}$	0.17	0.16	0.20	0.28	0.42
$\gamma_{\text{min}}$	$\frac{^{\circ}\text{C}}{100 \text{ ft}}$	-0.09	-0.10	-0.12	-0.12	-0.18
$\gamma_{\text{max}} - \gamma_{\text{min}}$	$\frac{^{\circ}\text{C}}{100 \text{ ft}}$	0.24	0.26	0.31	0.42	0.58
$\left  \frac{\Delta \gamma_L}{\Delta Z} \right $	$\frac{^{\circ}\text{C} (100 \text{ ft})^{-1}}{100 \text{ ft}}$	0.010	0.010	0.009	0.022	0.019
$WS_{\text{max}}$	$\text{ft sec}^{-1}$	122	125	134	138	142
$\bar{V}$	$\text{ft sec}^{-1}$	43	39	51	50	46
$\frac{\Delta \bar{V}}{\Delta Z}$	$\frac{\text{ft sec}^{-1}}{100 \text{ ft}}$	0.54	0.80	0.58	0.61	0.60
$\left( \frac{\Delta \bar{V}}{\Delta Z} \right)_{\text{lower}}$	$\frac{\text{ft sec}^{-1}}{100 \text{ ft}}$	0.59	0.38	0.68	0.70	0.57
$\left( \frac{\Delta \bar{V}}{\Delta Z} \right)_{\text{max}}$	$\frac{\text{ft sec}^{-1}}{100 \text{ ft}}$	0.75	0.92	0.83	0.84	0.86
$\bar{V} \cdot \frac{\Delta \bar{V}}{\Delta Z}$	$\frac{\text{ft}^2 \text{ sec}^{-2}}{100 \text{ ft}}$	26.7	35.1	31.9	35.0	36.3
$\left( \bar{V} \cdot \frac{\Delta \bar{V}}{\Delta Z} \right)_{\text{max}}$	$\frac{\text{ft}^2 \text{ sec}^{-2}}{100 \text{ ft}}$	43.5	39.1	54.6	40.6	53.6
R' imi	—	30	19	26	13	21

**TABLE 3-2**  
**AVERAGE VALUES OF METEOROLOGICAL VARIABLES FOR COMBINED**  
**TURBULENCE INTENSITY CATEGORIES—PHASE 2 and PHASE 3 DATA**

(Total Cases: Phase 2, 176 Cases; Phase 3, 195 Cases)

Variables*	CAT Intensity					
	None and very light		Light		Light to moderate and greater	
	Phase 2	Phase 3	Phase 2	Phase 3	Phase 2	Phase 3
$ \gamma $	0.07	0.08	0.10	0.08	0.12	0.10
$\gamma_{\max}$	0.15	0.17	0.19	0.20	0.22	0.36
$\gamma_{\min}$	-0.06	-0.09	-0.10	-0.12	-0.16	-0.16
$\gamma_{\max} - \gamma_{\min}$	0.21	0.24	0.29	0.31	0.38	0.52
$\left  \frac{\Delta \gamma_L}{\Delta Z} \right $	0.004	0.010	0.009	0.009	0.007	0.020
$WS_{\max}$	112	123	128	134	131	140
$\bar{V}$	43	42	56	51	62	48
$\frac{\Delta \vec{V}}{\Delta Z}$	0.46	0.57	0.62	0.58	0.69	0.61
$\left( \frac{\Delta \vec{V}}{\Delta Z} \right)_{\text{lower}}$	0.58	0.57	0.64	0.68	0.78	0.60
$\left( \frac{\Delta \vec{V}}{\Delta Z} \right)_{\max}$	0.70	0.77	0.81	0.83	0.97	0.85
$\bar{V} \cdot \frac{\Delta \vec{V}}{\Delta Z}$	21.2	27.8	31.6	31.9	40.8	35.8
$\left( \bar{V} \cdot \frac{\Delta \vec{V}}{\Delta Z} \right)_{\max}$	34.9	43.0	51.1	54.6	67.8	48.4
R'imi	37	29	25	26	11	18

\* The units are the same as in Table 3-1.

### Definition of Variables

The variables in the preceding tables are listed and described below:

$|\gamma|$  Absolute value of the lapse rate of the central layer. The central layer is defined as the layer that includes the reported occurrence on non-occurrence of turbulence. The layer is determined by the closest wind or temperature data, above and below the CAT occurrence level.

$\gamma_{\max}$  Maximum lapse rate within  $\pm 6500$  ft ( $\pm 2000$  m) of level of occurrence or non-occurrence.

$\gamma_{\min}$  Minimum lapse rate within  $\pm 6500$  ft of level of occurrence or non-occurrence of CAT.

$\gamma_{\max} - \gamma_{\min}$  Difference between the maximum and minimum lapse rates within  $\pm 6500$  ft of level of occurrence or non-occurrence of CAT.

$\left| \frac{\Delta\gamma_L}{\Delta Z} \right|$  Rate of change of lapse rate.

$WS_{\max}$  Maximum wind speed at any level.

$\bar{V}$  Mean wind speed of central layer.

$\frac{\Delta \vec{V}}{\Delta Z}$  Vertical vector wind shear of the central layer.

$\left( \frac{\Delta \vec{V}}{\Delta Z} \right)_{\text{lower}}$  Vertical vector wind shear of layer below central layer.

$\left( \frac{\Delta \vec{V}}{\Delta Z} \right)_{\max}$  Maximum vertical vector wind shear. The largest of the shears computed for a central layer or a layer above or below, provided the wind data is within  $\pm 6500$  ft of level of occurrence or non-occurrence of CAT.

$\bar{V} \cdot \frac{\Delta \vec{V}}{\Delta Z}$  Product of the mean wind speed and vertical vector shear of the central layer; in effect, the vertical gradient of kinetic energy.

$\left( \bar{V} \cdot \frac{\Delta \vec{V}}{\Delta Z} \right)_{\max}$  Maximum vertical gradient of kinetic energy within  $\pm 6500$  ft of level of occurrence.

$R'_{\text{imi}}$  Richardson Number based on minimum lapse rate within  $\pm 6500$  ft of level of occurrence.

The results from the Phase 3 data in Table 3-1 show more graphically than did the results from the Phase 2 data, that aircraft turbulence in the stratosphere is more directly related to meteorological variables computed from temperature rather than wind data. The association of CAT in the stratosphere with an irregular temperature profile, including particularly strong inversion layers, is seen clearly by comparing the average values of  $\gamma_{\max}$ ,  $\gamma_{\min}$  and  $\gamma_{\max} - \gamma_{\min}$  computed for no turbulence with those values computed for moderate and more intense CAT. Maximum temperature inversions with an average increase of  $0.42^{\circ}\text{C}$  per 100 ft were computed for intense CAT compared with  $0.17^{\circ}\text{C}$  per 100 ft for smooth flight. Similarly, the average values for minimum lapse rate were computed as  $-0.18^{\circ}\text{C}$  per 100 ft for intense CAT and  $-0.09^{\circ}\text{C}$  per 100 ft for no turbulence.

In contrast to the above results the average values of the variables computed from the wind data do not exhibit the same strong differences between no CAT and significant CAT. There is, to be sure, a tendency for higher values of the vertical vector wind shear and the vertical gradient of kinetic energy to correspond to turbulence occurrence. For example, the averages computed for  $\frac{\Delta \vec{V}}{\Delta Z}$  and  $\bar{V} \cdot \frac{\Delta \vec{V}}{\Delta Z}$  are  $0.60 \text{ ft sec}^{-1}$  per 100 ft and  $36.3 \text{ ft}^2 \text{ sec}^{-2}$  per 100 ft for moderate and more intense turbulence. The corresponding averages for smooth flight are  $0.54 \text{ ft sec}^{-1}$  per 100 ft and  $26.7 \text{ ft sec}^{-2}$  per 100 ft. The results in Table 3-1, however, clearly point to placing primary emphasis on the vertical variations of temperature and stability in the study of CAT occurrence in the stratosphere.

Averages were also computed for two subsets of the Phase 3 sample. In the first subset all cases in the Panama area and in the vicinity of convective activity were removed. The second subset comprised those cases which had previously been selected as independent data tests.

The results can be conveniently summarized briefly without presenting the averages computed. For most of the 13 variables the exclusion of the cases of convective activity did not result in strikingly different results. This is particularly true of the variables derived from the temperature data and corroborates the impressions obtained from the case studies that the turbulence in the stratosphere encountered in the vicinity of convective activity is often associated with an irregular temperature profile frequently possessing many of the same characteristics (e.g., double-inversion

structure tendency) associated with CAT. The removal of the convective cases tended to further reduce the differences between the average values of variables derived from the wind data for no turbulence compared with significant CAT. It might also be noted that when the five cases of turbulence defined from the Panama flights only were excluded (all of "light to moderate or greater intensity," under conditions of light wind flow near flight level) there was a modest increase in the average values computed for the categories of "light to moderate turbulence" and "moderate or greater turbulence" for the 3 variables affected by the mean wind speed of the central layer.

It is important to compare the results obtained from the HICAT Phase 2 and Phase 3 data samples prior to combining them for an overall evaluation. The Phase 2 flights were conducted largely in 1966 and the Phase 3 flights in 1967 and the first two months of 1968. The Phase 2 flights included sampling over the Pacific Ocean near Hawaii, the Caribbean and Alaska. Phase 3 flights were conducted over the south central United States, the southeast United States and Panama. Both phases included extensive flying over the western United States and the northeastern United States. While flights in both phases were conducted during all seasons of the year more flying occurred in the vicinity of regions of convective activity during the Phase 3 period.

In comparing the results obtained from the analysis of the radiosonde data in the Phase 2 and Phase 3 periods we are concerned with both identifying consistent relationships and also noting when minor or major deviations are present. In a sense, the Phase 3 data may be considered an independent test of the results obtained from the Phase 2 sample and the inverse is also true. The average values of the meteorological variables computed for three categories of CAT from the Phase 2 sample compared with those computed from the Phase 3 sample are shown in Table 3-2.

Two conclusions are very clear after examining Table 3-2. The first four variables derived from the temperature data discriminate well between "none and very light turbulence," and "light to moderate and greater turbulence," for both Phase 2 and 3 data samples. The differences between the averages computed for  $|\gamma|$  and  $\gamma_{\min}$  are less for the Phase 3 data. On the other hand, the differences computed from the Phase 3 data for  $\gamma_{\max}$  and  $\gamma_{\max} - \gamma_{\min}$  are larger. Thus, in summary, the first four variables in the table which depict the key vertical temperature lapse

rate characteristics and variability discriminated well between smooth flight and significant turbulence during both the Phase 2 and Phase 3 HICAT test flights.

In comparing the average values computed for several measures of the vertical gradient of wind shear and kinetic energy one must conclude that the Phase 2 and Phase 3 results are different in regard to the strength of the relationship with CAT intensity. For each of the variables shown, the differences in the averages computed are much less for the Phase 3 sample. Obviously, this result requires further assessment regarding the utility of stratospheric wind data derived from standard rawinsonde observations.

#### Average Values for CAT Categories: Phase 2 and 3 Combined

The average values of the 13 variables computed for the three-category CAT intensity breakdown is shown for all cases in the combined Phase 2 and Phase 3 samples in Table 3-3.

Some comments on the overall results follow:

(a) Absolute value of lapse rate in the central layer  $|\gamma|$ . The value (in °C per 100 ft) of 0.08 for "none and very light CAT" is somewhat less than 0.11 obtained for "light to moderate or more intense CAT." This result points to the conclusion that large positive or negative lapse rates are associated with significant CAT; a conclusion more clearly substantiated by considering variations in the lapse rate.

(b) Maximum lapse rate ( $\gamma_{\max}$ ). The averages computed in °C per 100 ft clearly substantiate the association of CAT with significant inversion layers. The value of 0.29 for moderate CAT is nearly double that computed for the non-turbulence cases.

(c) Minimum lapse rate ( $\gamma_{\min}$ ). The average value in °C per 100 ft computed for light to moderate or greater CAT of -0.16 contrasts with the average of -0.08 computed for "no CAT and very light CAT." A layer with a significant negative lapse rate in the stratosphere where the overall lapse rate is generally positive or nearly isothermal clearly contributes to an irregular temperature profile. The minimum Richardson Number computed with this lapse rate ( $R'_{\min}$ ) has an average value of 32.3 for "no turbulence and very light CAT" and only 14.6 for light to moderate or greater CAT.



TABLE 3-3  
AVERAGE VALUES OF METEOROLOGICAL VARIABLES FOR  
COMBINED TURBULENCE INTENSITY CATEGORIES—ALL CASES

(Total Cases: 371)

Variables	CAT Intensity Category		
	None and very light $g <  \pm 0.10 $	Light $ \pm 0.10  \leq g <  \pm 0.25 $	Light to moderate or greater $g \geq  \pm 0.25 $
$ \gamma $	0.08	0.09	0.11
$\gamma_{\max}$	0.16	0.19	0.29
$\gamma_{\min}$	-0.08	-0.11	-0.16
$\gamma_{\max} - \gamma_{\min}$	0.23	0.30	0.45
$\left  \frac{\Delta \gamma_L}{\Delta Z} \right $	0.008	0.009	0.011
$WS_{\max}$	117	132	137
$\bar{V}$	42	54	55
$\frac{\Delta \vec{V}}{\Delta Z}$	0.52	0.60	0.65
$\left( \frac{\Delta \vec{V}}{\Delta Z} \right)_{\text{lower}}$	0.57	0.66	0.68
$\left( \frac{\Delta \vec{V}}{\Delta Z} \right)_{\max}$	0.74	0.82	0.91
$\bar{V} \cdot \frac{\Delta \vec{V}}{\Delta Z}$	24.8	31.8	38.5
$\left( \bar{V} \cdot \frac{\Delta \vec{V}}{\Delta Z} \right)_{\max}$	39.3	52.8	58.0
R' imi	32.3	25.6	14.6

(d) The difference between the maximum and minimum lapse rates ( $\gamma_{\max} - \gamma_{\min}$ ), expressed in °C per 100 ft discriminates well among the categories of "none and very light," "light," and "light to moderate or greater" CAT. The respective values are 0.23, 0.30, and 0.45. This result is strong evidence that the degree of irregularity of the temperature lapse rate is directly related to intensity.

(e) A measure of the rate of change of lapse rate  $|\Delta\gamma_L/\Delta Z|$  gives some further indication that changes in the slope of the vertical temperature profile are larger when significant CAT is present.

(f) Maximum wind speed  $(WS)_{\max}$  and mean wind speed of the central layer ( $\bar{V}$ ). The maximum wind speed usually is found between 30,000 to 40,000 ft and is only indirectly related to CAT in the stratosphere. Both for this variable and the mean wind speed at the level of CAT occurrence there is a fairly significant increase in the averages computed for light CAT as compared to smooth flight and very light turbulence. Little further increase in speed, however, is noted for more significant CAT.

(g) Vertical vector wind shear of central layer  $(\Delta \vec{V}/\Delta Z)$ . CAT in the upper troposphere has probably been more consistently associated with the vertical vector shear of the horizontal wind than any other single meteorological variable. The association with CAT in the stratosphere is not as strong although there is a tendency for somewhat larger values of vertical vector wind shear to be related to significant CAT. The degree of correlation is about the same for the vertical vector wind shear of the lower layer  $(\Delta \vec{V}/\Delta Z)_{\text{lower}}$  and for the maximum vertical vector wind shear  $(\Delta \vec{V}/\Delta Z)_{\max}$ .

(h) Vertical gradient of kinetic energy  $(\bar{V} \cdot \Delta \vec{V}/\Delta Z)$ . Expressed in units of  $\text{ft}^2 \text{sec}^{-2}$  per 100 ft, large vertical gradients of energy indicate a potential for considerable energy exchange in the vertical with consequent perturbations or fluctuations of the flow and CAT. The value of 38.5 for light to moderate and moderate CAT contrasts with the average value of 24.8 computed for non-turbulence cases. The maximum gradient of kinetic energy  $(\bar{V} \cdot \Delta \vec{V}/\Delta Z)_{\max}$  is similarly related to CAT except that the average values are more than 50% larger.

### Comparison of Tropospheric and Lower Stratospheric Characteristics

A large number of research studies over the past 15 years have concentrated on relating values of meteorological variables determined from temperature and wind soundings to CAT occurrence in the upper troposphere. In the majority of cases routine operational radiosonde and rawinsonde data were used. While results frequently indicated a relationship between parameters measuring vertical wind shear or stability variations and turbulence the degree of the correlations was often modest.

In view of the extent of previous research with synoptic data in the upper troposphere it was deemed advisable to devote only a small portion of our current effort to this aspect of CAT research. A principal objective of this portion of our study was to obtain values of meteorological variables associated with subjective tropospheric CAT for comparison with the values obtained in association with CAT in the stratosphere. The formulation of the variables, computational procedures, and data format are the same in both sets of computations. It should be remembered that the tropospheric sample is from the January to June 1966 period in the United States while the stratospheric sample encompasses a longer time period and a greater variety of geographic locations. In spite of these differences it is worthwhile to at least briefly compare the average values obtained in the two sets of computations.

The average values of eight variables associated with CAT in the upper troposphere (generally between 30,000 and 37,000 ft) are given in Table 3-4. The values and the number of cases on which the computations are based are given for intensities of "light-to-moderate," "moderate or greater" and combined "light-to-moderate or greater." These values may be compared with those obtained in the stratosphere as given in Table 3-3.

An examination of Table 3-4 shows that there is little systematic variation between the values obtained for light moderate intensities (19-22 cases) as compared to the values obtained for moderate or greater intensities (24 or 25 cases). This is understandable since the sample size is small, the intensities are subjectively determined and the CAT intensity characterizing each case is the most representative of at least 3 to 5 subjective reports. All cases of CAT of "light to moderate or greater intensity" are therefore combined in the table for comparison with computations from stratospheric data.

TABLE 3-4  
AVERAGE VALUES OF METEOROLOGICAL VARIABLES  
ASSOCIATED WITH CAT IN THE UPPER TROPOSPHERE

Variable	CAT Intensity					
	Light to Moderate		Moderate or Greater		Combined Intensities	
	Average	Number of cases	Average	Number of cases	Average	Number of cases
$\frac{\Delta \vec{V}}{\Delta Z}$	0.825	19	0.642	24	0.723	43
$\bar{V} \cdot \frac{\Delta \vec{V}}{\Delta Z}$	117.4	19	90.2	24	102.3	43
$\bar{V}$	161	19	118	24	138	43
$WS_{\max}$	194	20	141	24	164	44
$\gamma$	-0.213	22	-0.176	25	-0.194	47
$\gamma_{\max} - \gamma_{\min}$	0.333	22	0.398	25	0.367	47
$\gamma_{\min}$	-0.236	22	-0.248	25	-0.243	47
$\gamma_{\max}$	0.096	22	0.113	25	0.105	47

A comparison of Tables 3-3 and 3-4 shows that the average values associated with "light to moderate and greater" CAT vary as follows:

- (a) The vertical vector wind shear values in the upper troposphere are somewhat larger than those computed in the stratosphere.
- (b) The average values of mean wind speed and vertical gradient of kinetic energy are more than twice as large in the upper troposphere. However, note that the average value of maximum wind speed is about  $30 \text{ ft sec}^{-1}$  greater for the tropospheric sample reflecting a higher percentage of winter-middle latitude cases.
- (c) The several measures of lapse rate reflect the obvious difference in stability between the troposphere and stratosphere, with the minimum lapse rate in the troposphere being more negative and the maximum lapse rate less positive. It is worth noting that the average value of the difference between the maximum and minimum lapse rates within  $\pm 6500 \text{ ft}$  of the level of CAT occurrence was very similar for both samples.

### Lower Stratospheric Meteorological Relationships

Another method of determining the relationship between categories of CAT and meteorological variables is to determine the distribution of CAT occurrences for the sample stratified according to prescribed ranges of a variable. The results obtained from a three-category classification are shown for six variables in Table 3-5. The distribution is given for three categories of CAT grouped as "none and very light," "light," and "light to moderate or greater." The sums of the number of cases will not agree among variables because of missing data. The variables are listed in order of decreasing percentage of hits. The category limits were chosen by considering both the mean category values given in Table 3-3 and the distribution of the individual values tabulated by turbulence category.

An examination of Table 3-5 indicates that all variables show a significantly different distribution of cases in the three CAT categories. The best example of this is seen with the variable  $\gamma_{\max} - \gamma_{\min}$ . For values less than 0.27°C per 100 ft, only 24 of 205 cases (11.7%) possess "light to moderate or greater" intensity while for values greater than 0.43°C per 100 ft, 31 of 77 cases (40.3%) exhibit this same intensity. Similar results are obtained with  $R'_{\text{imi}}$ . When the minimum Richardson Number is greater than 15, 14 of 146 (9.6%) are significantly turbulent while with  $R'_{\text{imi}}$  less than 3.5 the percentage increases to 39.3%. It is also apparent from examining the table, that while good results can be obtained in specifying CAT of "none or very light" intensity and also CAT of significant intensity, it is not possible to specify a range of values of a variable that will correspond to a high likelihood of encountering light CAT. Since light CAT represents the transitional atmospheric condition it is not of high importance to aircraft operation.

A chi square test was applied to the category distributions of each of the contingency tables. This test is a simple, and only an approximate means of evaluating the relative strength of the relationships between the categorized variables and the three categories of CAT. It essentially measures the departure of the actual category distribution from that number which would be expected, based on the row and column totals of the table. Allowing for the proper degrees of freedom (four for a  $3 \times 3$  matrix) one can then reject the hypothesis that the actual distribution was due to chance for a given confidence level. At the 5% and 1% confidence level one can state that the

TABLE 3-5

CONTINGENCY TABLE COMPARISON OF METEOROLOGICAL VARIABLES AND  
CLEAR AIR TURBULENCE CASES—PHASES 2 and 3 DATA

Variable	Category limits	Turbulence Intensity			Number of cases	Total cases	Percent hits	Chi square
		None and very light $g <  \pm 0.10 $	Light $ \pm 0.10  \leq g <  \pm 0.25 $	Light moderate or greater $g \geq  \pm 0.25 $				
$\gamma_{\max} - \gamma_{\min}$	$< 0.27^{\circ}\text{C}/100 \text{ ft}$	137	44	24	205	370	50.3	38.6
	$0.27-0.43$	48	18	22	88			
	$> 0.43$	23	23	31	77			
$\gamma_{\max}$	$< 0.15^{\circ}\text{C}/100 \text{ ft}$	128	39	29	196	371	49.3	21.1
	$0.15-0.25$	42	22	15	79			
	$> 0.25$	39	24	33	96			
R' imi	$> 15$	98	34	14	146	348	48.9	31.8
	$3.5-15$	65	27	21	113			
	$< 3.5$	35	19	35	89			
$\gamma_{\min}$	$> -0.10^{\circ}\text{C}/100 \text{ ft}$	125	38	20	183	371	48.4	33.6
	$-0.10- -0.17$	52	21	24	97			
	$< -0.17$	32	25	34	91			
$\frac{\Delta \bar{V}}{\Delta Z}$	$< 0.6 \frac{\text{ft sec}^{-1}}{100 \text{ ft}}$	122	42	37	201	348	47.4	13.5
	$0.6-0.8$	43	18	7	68			
	$> 0.8$	33	21	25	79			
$\bar{V} \cdot \frac{\Delta \bar{V}}{\Delta Z}$	$< 23 \frac{\text{ft}^2 \text{sec}^{-2}}{100 \text{ ft}}$	110	36	32	178	336	45.5	16.7
	$23-40$	41	15	8	64			
	$> 40$	37	29	28	94			

distribution is not due to chance if chi square equals or exceeds 9.5 and 13.3 respectively. It should be remembered that each element of the contingency table is given equal weight while actually we are most concerned with the ability of a particular variable within a given range of values to isolate cases of significant CAT of at least light to moderate intensity in the stratosphere.

Table 3-5 generally confirms what one might expect from the previously discussed average values obtained from each CAT category. The difference between the maximum and minimum lapse rate  $\gamma_{\max} - \gamma_{\min}$  has both the highest percentage of hits (50.3%) and the largest chi square value (38.6). The percentage of hits and the chi square values of the related variables  $\gamma_{\max}$ ,  $R'_{\text{imi}}$ , and  $\gamma_{\min}$  are measurably higher than the values obtained for the wind-derived variables  $\Delta \vec{V} / \Delta Z$  and  $\bar{V} \cdot \Delta \vec{V} / \Delta Z$ . The vertical vector wind shear and the vertical gradient of kinetic energy are related to the occurrence of CAT in the stratosphere but the relationship is weaker than that obtained with the temperature-derived variables.

An extension of this type of analysis is to study the relationship between CAT occurrence and combinations of the variables considered jointly. The analysis is restricted to evaluating the ability of combinations of two variables to specify three intensity categories: none and very light, light, and light to moderate or greater. For each of the paired variables considered the intensities of all cases were plotted with the location being determined by the joint values of the variables. After examining the distributions and clusterings of like intensities the following three sectors were delineated:

Sector I—Little likelihood of CAT and, if encountered, the intensity is light

Sector II—Increased frequency of encountering CAT but the intensity is most often light

Sector III—CAT is likely to be experienced and it will be of light to moderate or greater intensity

Considering both the Phase 2 and Phase 3 samples the corresponding numerical data are shown in Table 3-6 and graphs are given in Figs. 3-1, 3-2 and 3-3. The variable combinations given are  $(\gamma_{\max} - \gamma_{\min})$  vs.  $R'_{\text{imi}}$ ,  $\gamma_{\max}$  vs.  $\gamma_{\min}$ , and  $(\bar{V} \cdot \Delta \vec{V} / \Delta Z)$  vs.  $\gamma_{\max}$ .

TABLE 3-6  
CONTINGENCY TABLE COMPARISON OF JOINT VARIABLES AND  
CLEAR AIR TURBULENCE CASES—PHASES 2 AND 3 DATA

Variable	Sector category	Turbulence intensity			Number of cases	Total cases	Percent hits	Chi square
		None and very light $g <  \pm 0.10 $	Light $ \pm 0.10  \leq g <  \pm 0.25 $	Light to moderate or greater $g \geq  \pm 0.25 $				
$\gamma_{\max} - \gamma_{\min}$ vs. R' imi	I	131	38	15	184	345	56.5	58.0
	II	24	20	10	54			
	III	40	23	44	107			
$\gamma_{\max}$ vs. $\gamma_{\min}$	I	147	44	26	217	367	54.2	37.9
	II	26	15	11	52			
	III	36	25	37	98			
$\bar{V} \cdot \frac{\Delta \bar{V}}{\Delta Z}$ vs. $\gamma_{\max}$	I	151	48	31	230	346	56.9	37.1
	II	22	23	16	61			
	III	22	10	23	55			



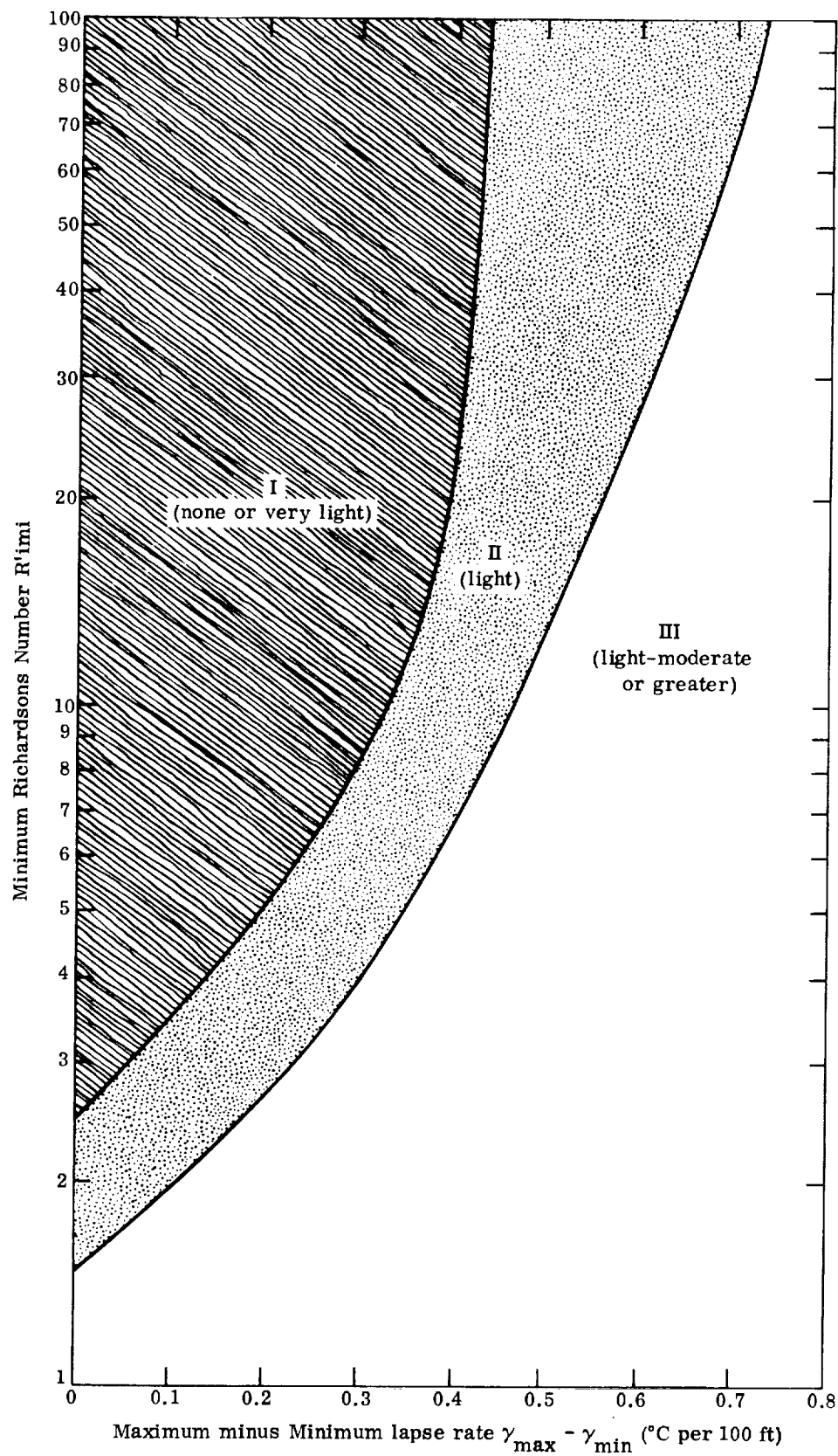


Fig. 3-1. Graph of  $R'_{imi}$  vs  $(\gamma_{max} - \gamma_{min})$  for encountering CAT of given intensity.

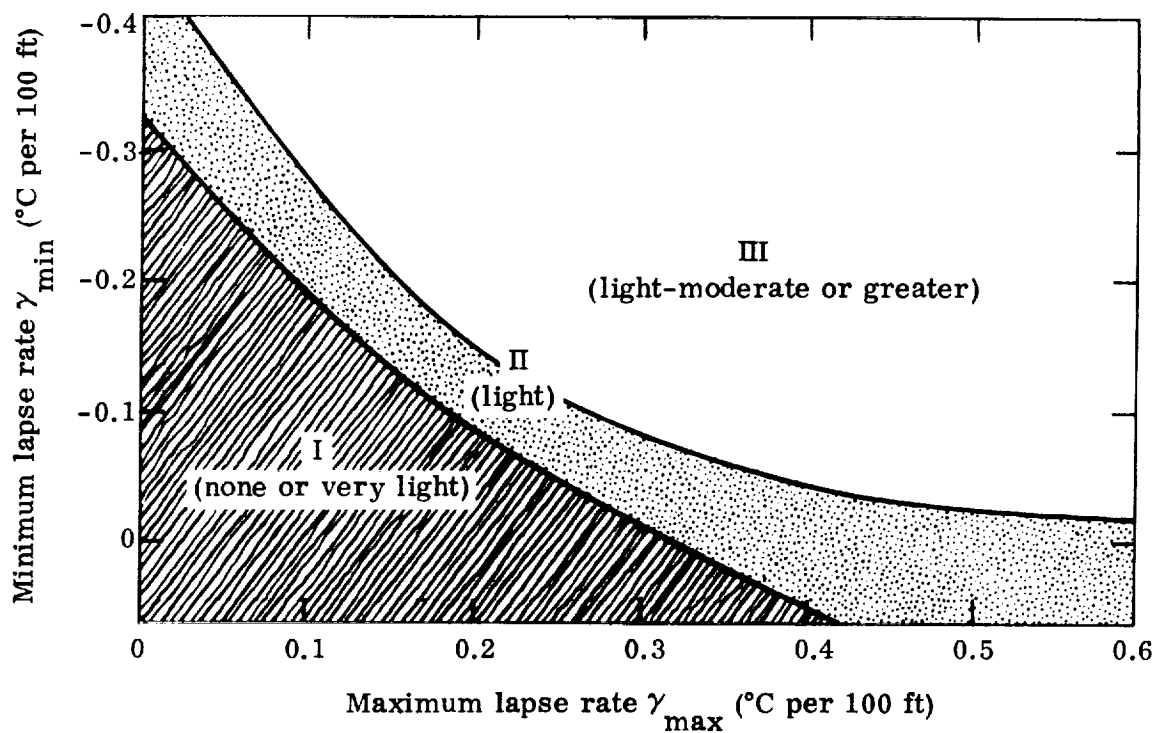


Fig. 3-2. Graph of  $\gamma_{\min}$  vs  $\gamma_{\max}$  for encountering CAT of given intensity.

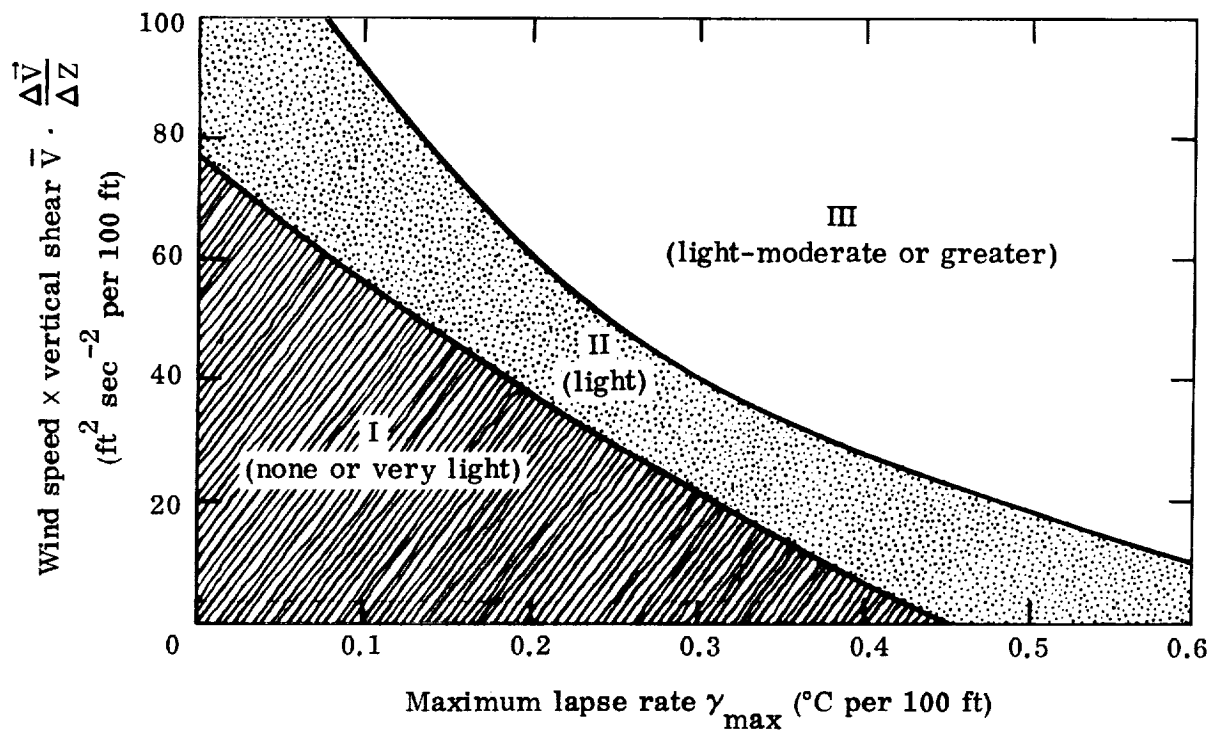


Fig. 3-3. Graph of  $\bar{V} \cdot \frac{\Delta \bar{V}}{\Delta Z}$  vs  $\gamma_{\max}$  for encountering CAT of given intensity.

The chi square test showed that the most significant relationship was obtained with  $(\gamma_{\max} - \gamma_{\min})$  vs.  $R' \text{ imi}$  (plotted on a semi-logarithmic scale). The chi square value of 58.0 was considerably higher than the values obtained for the distributions with either variable alone (38.6 and 31.8). The percent hits also increased by 6.2% and 7.6% over that obtained with the individual variables. Equally important, the Phase 2 and Phase 3 samples were very consistent with this variable combination where the percent hits were 55.8% and 57.2%, respectively. The combination of these two variables effectively considers both a measure of lapse rate irregularity  $(\gamma_{\max} - \gamma_{\min})$  and a measure of stability ( $R' \text{ imi}$ ) including the effect of vertical vector wind shear when large values of shear become significant. Figure 3-1 shows that Sector III is defined at endpoints by  $R' \text{ imi} \leq 1.5$  and  $(\gamma_{\max} - \gamma_{\min}) \geq 0.7^\circ\text{C per 100 ft.}$  As  $R' \text{ imi}$  increases, larger values of  $(\gamma_{\max} - \gamma_{\min})$  are required if light to moderate or more intense CAT is to be expected.

The results obtained, considering only the temperature data as reflected by  $\gamma_{\max}$  vs.  $\gamma_{\min}$ , were nearly as good in terms of percent hits and consistency between the Phase 2 and Phase 3 samples. The third variable combination  $(\bar{V} \cdot \Delta\vec{V}/\Delta Z)$  vs.  $\gamma_{\max}$  appears to be quite satisfactory with the percent hit score of 56.9%. There are, however, serious problems associated with its application for specifying more intense CAT. A significant number of cases of intense CAT in the stratosphere were not associated with either high wind speeds or large vertical wind shear as measured by standard rawinsonde equipment. This was particularly evident in the Phase 3 sample. This factor influences in two ways the results obtained with  $\bar{V} \cdot \Delta\vec{V}/\Delta Z$  vs.  $\gamma_{\max}$ . First, for the entire sample, significant CAT is underspecified and secondly, the results obtained with the Phase 3 data are inferior. The percent hits decreases from 61.0% (Phase 2) to 53.3% (Phase 3) and only 10 cases of light to moderate or more intense CAT are correctly specified in the Phase 3 sample.

Therefore, the analysis of variable combinations showed that the most consistent and useful results were obtained when temperature-derived variables were considered along or were dominant in the relationship. The combination  $(\gamma_{\max} - \gamma_{\min})$  vs.  $R' \text{ imi}$  (determined from  $\gamma_{\min}$  and  $\Delta\vec{V}/\Delta Z$ ) yielded the most significant results (largest value of chi square).

### Case Studies

The statistical summaries of meteorological variables, circulation features and satellite-observed cloud features provide the basic data for interpretation and generalization of guidelines to isolate regions in the stratosphere in which CAT is most likely to occur. A more intensive study of particular cases can provide considerable understanding of the mechanisms producing CAT and help in the concrete formulation of guidelines to predict phenomenon. The dates selected from the Phase 2 sample are: April 1, 1966; May 13, 1966; August 24, 1966; August 29, 1966; September 30, 1966; October 20, 1966; October 24, 1966; and October 28, 1966. The dates studied from the Phase 3 sample are: March 13, 1967; May 2-3, 1967; May 16, 1967; July 5-7, 1967; September 11, 1967; September 19-21, 1967; and November 28-December 2, 1967. Three examples from the Phase 3 sample are discussed to illustrate some of the findings.

In studying individual cases we can simultaneously consider the vertical variations in temperature and wind data from radiosonde observations and the synoptic-scale features from analyses of upper-level constant-pressure surfaces along with cloud characteristics as seen from weather satellite pictures. The joint examination of both the larger-scale meteorological features and cloud characteristics in conjunction with the smaller-scale sounding data contributes to an understanding of the mechanisms involved in CAT occurrence and the requirements for developing successful airborne detection systems.

#### March 13, and 14, 1967 (Moderate Turbulence)

HICAT research flight test No. 180 was conducted from Edwards AFB, California to Hanscom Field, Bedford, Massachusetts during the time period 1810-2350 GMT. The flight track (shown in Fig. 3-4) passed over the states of Utah, Colorado, Nebraska, Iowa, Illinois, Michigan, and New York. Moderate to severe CAT was encountered at the 61,000 ft level over Colorado and moderate CAT occurred over Nebraska at the same level with light turbulence experienced over Michigan.

At 1800 GMT on the surface a frontal system dominates the central part of the country with four distinct, relatively weak, low pressure centers located in Nevada, Wyoming, Missouri, and Michigan. High pressure ridges and anticyclonic flow occupy much of the east coast and the plain states north of 40°N latitude.

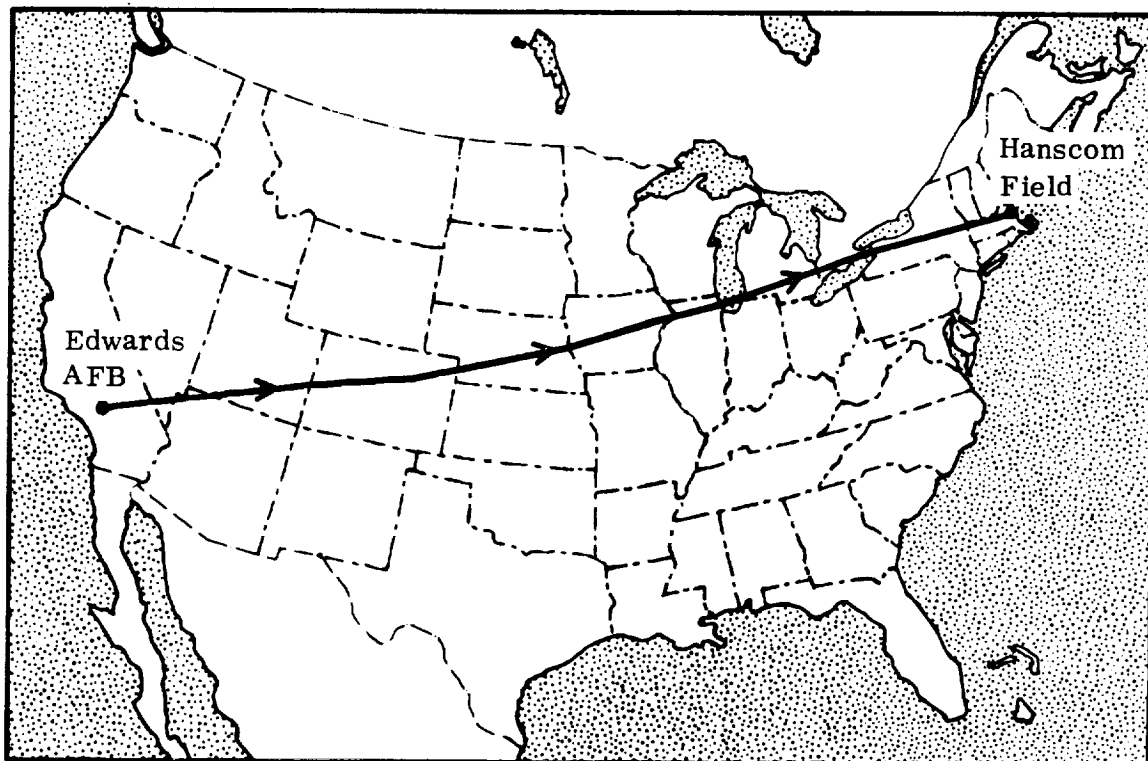


Fig. 3-4. HICAT research flight test no. 180 on March 13, 1967 (1810-2350 GMT) [21].

On March 14, at 0000 GMT, a pronounced trough is located just off the Pacific coast on the 300-mb constant pressure surface (about 30,000 ft altitude) with resulting strong southwesterly flow over the Rocky Mountain states and near-westerly flow over almost the entire United States west of 105°W longitude. The wind speeds at 300-mb below the flight track are high (e.g., Grand Junction, Colorado 200 ft sec<sup>-1</sup>; Denver, Colorado, 174 ft sec<sup>-1</sup>; Omaha, Neb., 164 ft sec<sup>-1</sup>; Flint, Mich., 184 ft sec<sup>-1</sup> and Albany, N. Y., 144 ft sec<sup>-1</sup>).

On March 14 at 0000 GMT, the contour pattern on the 100-mb constant pressure surface (about 53,000 ft altitude) is quite similar to that at the 300-mb level with the most significant feature being a pronounced trough off the Pacific coast. The smooth analysis indicates generally moderate horizontal temperature gradients. Wind speeds are greatly reduced from those measured at the 300-mb surface indicating large vertical wind shear (e.g., Grand Junction, 66 ft sec<sup>-1</sup>; Denver, 56 ft sec<sup>-1</sup>; Omaha, 56 ft sec<sup>-1</sup>).

A total of nine cases were defined from this lengthy flight. Four of these cases involved CAT with intensities of light to moderate or greater. The two most interesting cases are shown in Figs. 3-5(a) and 3-5(b).

Fig. 3-5(a) shows that light to moderate CAT was encountered over Denver, Colorado in a layer just above a temperature inversion layer. The temperature profile above the 125-mb level is extremely irregular including both strong inversion layers and layers in which the temperature decreases rapidly with height. Within 6500 ft of flight level the maximum and minimum lapse rates are 1.36°C and -0.27°C per 100 ft, respectively. A minimum Richardson Number of 1.30 was computed.

Moderate CAT measured 85 miles from North Platte, Nebraska is also located close to a temperature inversion layer as can be seen in Fig. 3-5(b). Again, an irregular vertical temperature lapse rate within ±6500 ft of flight level is demonstrated with maximum and minimum values of 0.43°C and -0.12°C per 100 ft computed. In both cases the vertical vector wind shear of the horizontal wind was small near flight level, which is indicative of the large vertical separation from the tropopause surface. The maximum wind speeds of 213 ft sec<sup>-1</sup> at Denver, and 200 ft sec<sup>-1</sup> at North Platte, however, reflect the closeness (in the horizontal) of the jet stream to the flight track and

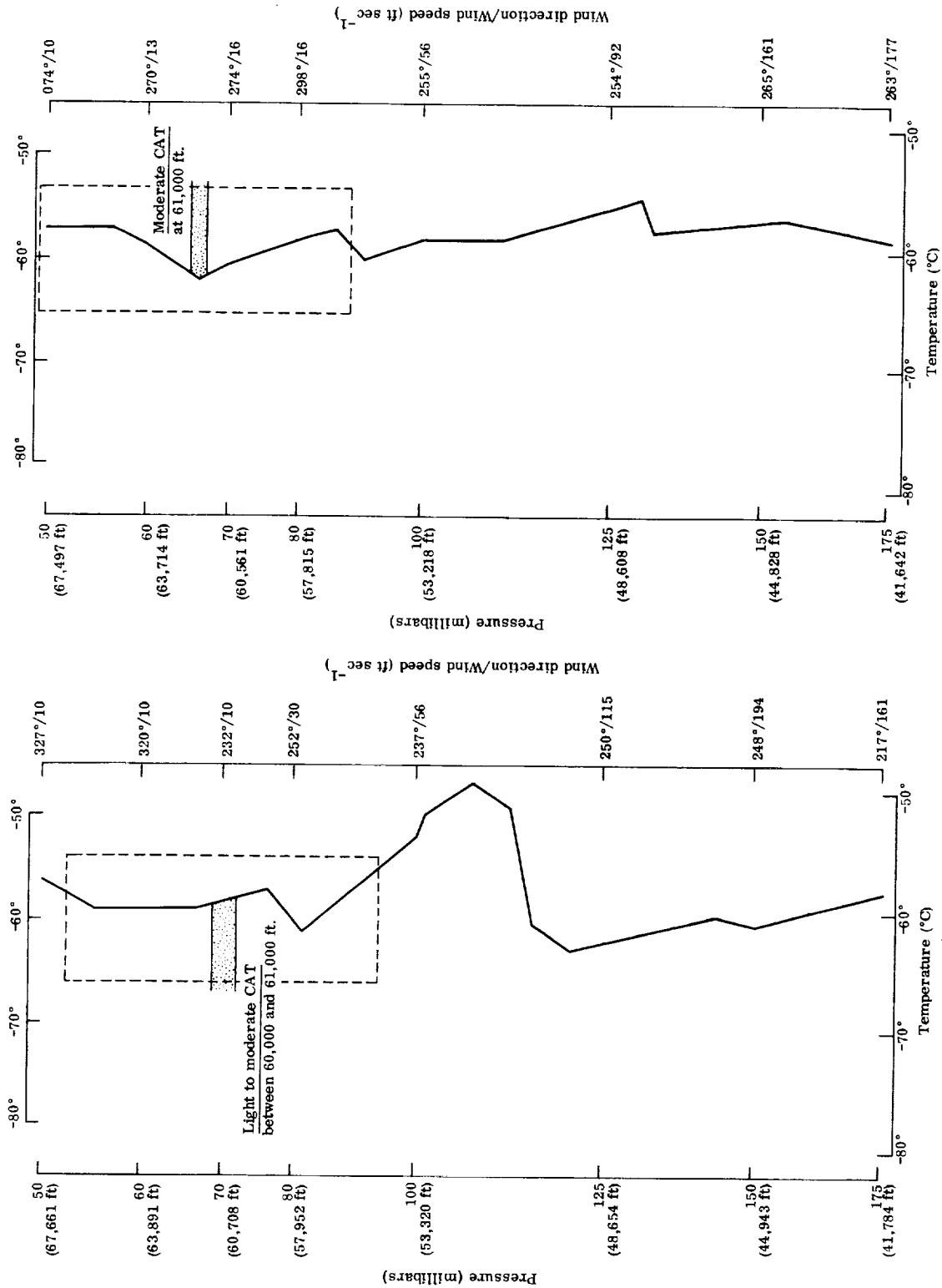


Fig. 3-5(a). Temperature and wind sounding at Denver, Colorado on March 14, 1967 (0000 GMT). The light to moderate turbulence was reported near the sounding location and was encountered 4 hours prior to the observation.

Fig. 3-5(b). Temperature and wind sounding at North Platte, Nebraska on March 14, 1967 (0000 GMT). The moderate turbulence was reported about 85 miles from the sounding location and was encountered 3 hours prior to the observation.

consequently the very large vertical wind shears present in the lowest levels of the stratosphere.

In contrast to the western portion of the flight only none or light CAT was encountered by the U-2 aircraft over the northeastern United States. For example; over Albany, New York, no CAT of any intensity was observed. The temperature profile was smooth in the region about the estimated flight level of 55,000 ft. In fact, the computed maximum and minimum lapse rates were only  $-0.03^{\circ}\text{C}$  and  $-0.09^{\circ}\text{C}$  per 100 ft and no temperature inversion layers were detected close to the flight level.

It is interesting to compare a vertical cross section of potential temperature in the western United States with one in the eastern United States. A cross section of potential temperature from Grand Junction, Colorado to Omaha, Nebraska is shown in Fig. 3-6(a) and a similar cross section from Flint, Michigan to Albany, New York is given in Fig. 3-6(b). The isentropes are drawn every  $5^{\circ}\text{A}$  and the flight level is shown by a dashed line. Some obvious differences are noted below the flight level. In the western United States where CAT was encountered the isentropes have non-uniform slopes with regions of packing and spreading. This is indicative of an irregular vertical temperature profile and sloping baroclinic layers associated with CAT. In contrast to this where no turbulence was experienced between Flint and Albany, the isentropes in the eastern United States exhibit little slope and are uniform in appearance with gradual variation in the vertical gradient.

In short, CAT of significant intensity encountered over the western United States occurred in southwesterly flow ahead of an upper level trough at both the 300-mb and 100-mb levels. An irregular temperature profile including pronounced temperature inversions was observed near flight level and wind speeds and vertical shears were small which reflect the large distances from the tropopause. However, large maximum wind speeds near the tropopause indicate the proximity of the jet stream and large shears in the lower stratosphere. In contrast to the above the absence of CAT over New York State was related to a smooth vertical temperature profile.

#### September 11, 1967 (No Turbulence)

HICAT research flight test No. 241 was conducted from Patrick AFB, Florida on September 11 between 1410 GMT and 1946 GMT. Both the outbound and return legs



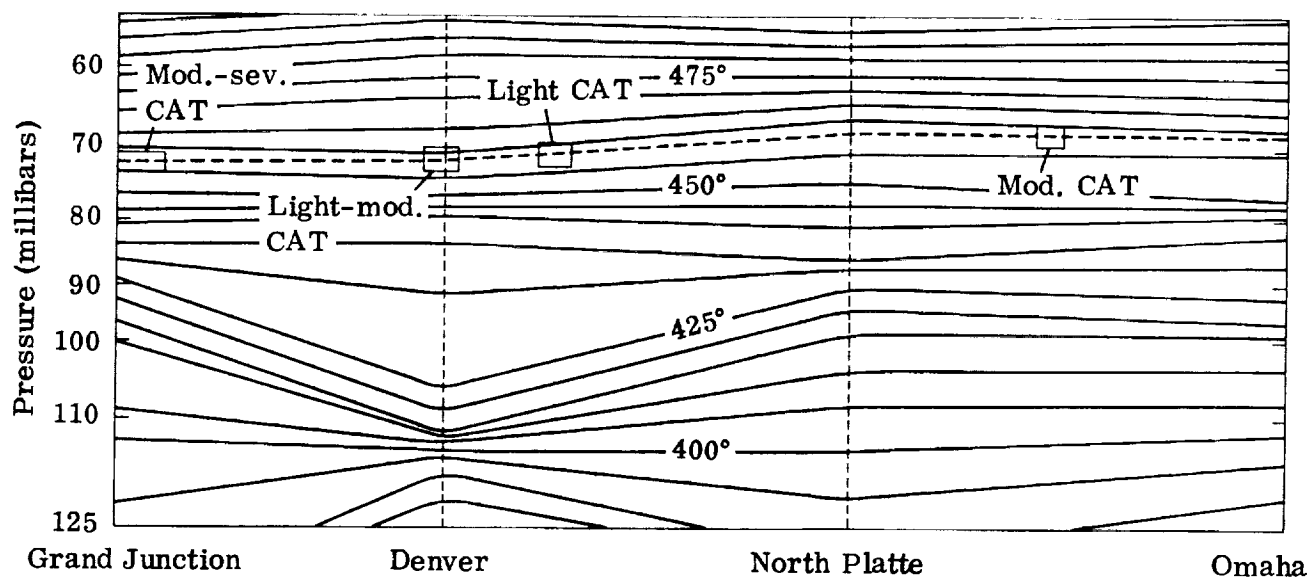


Fig. 3-6(a). Vertical cross section of potential temperature from Grand Junction, Colorado to Omaha, Nebraska on March 14, 1967 at 0000 GMT.

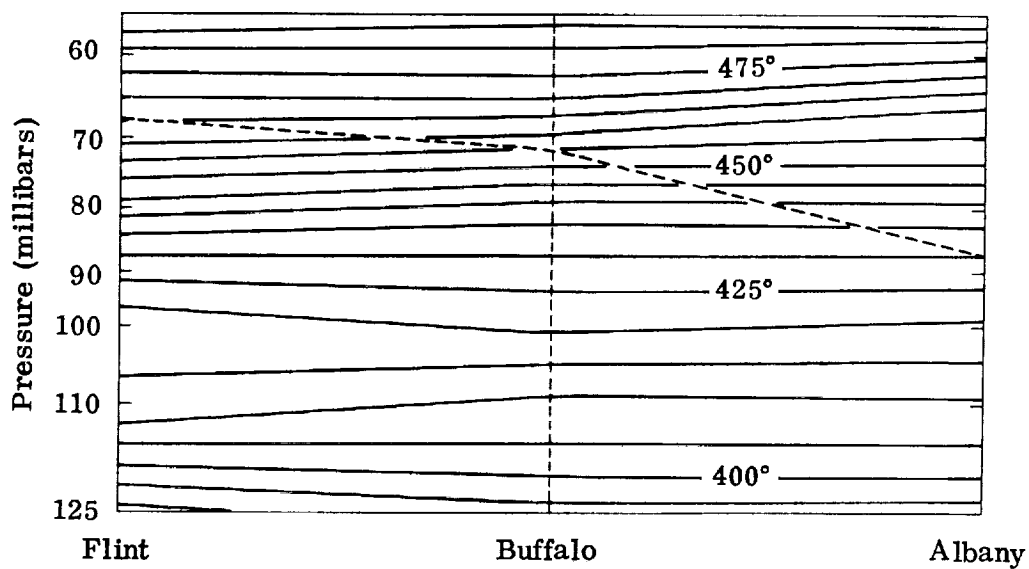


Fig. 3-6(b). Vertical cross section of potential temperature from Flint, Michigan to Albany, New York on March 14, 1967 at 0000 GMT.

of the flight track were along the Atlantic Coast from 28°N to 37°N latitude where no turbulence was encountered. Only very light CAT was encountered over the Atlantic Ocean near the center of Hurricane Doria at 37°N, 71°W. This absence of turbulence was typical of most HICAT flights in the southeastern United States during September and October 1967.

Apart from Hurricane Doria, the principal feature at the surface at 1200 GMT was a cold front extending southwest from about 100 miles off Cape Hatteras into central Georgia. On September 12 (0000 GMT) at 300-mb a weak low-contour center was located in the Mississippi Valley and southern Appalachians in conjunction with an extension of the Bermuda High to the south of Florida which produced light (less than  $80 \text{ ft sec}^{-1}$ ) southwesterly flow along the coast south of 35°N. The flow was west-northwest above this latitude under the influence of the trough over the Atlantic associated with Hurricane Doria. At the 100-mb level both wind speeds and horizontal temperature gradients are very small with a ridge covering the southern United States.

The ESSA 2 APT mosaic for September 11 shows that Florida was relatively cloud-free. Coastal Georgia, South Carolina and North Carolina are at the western edge of banded frontal cloudiness that extended to the northeast and merged with the spiral-banded cloud circulation of Hurricane Doria.

Cases of no turbulence at an estimated altitude of 55,000 ft were associated with radiosonde observations taken at 1200 GMT on September 11 at Jacksonville, Florida; Charleston, South Carolina; Cape Hatteras, North Carolina and Wallops Island, Virginia. Each temperature sounding at the four locations was very smooth from the 400-mb to 50-mb constant-pressure surfaces. The soundings taken at Jacksonville, Florida and Charleston, South Carolina are shown in Figs. 3-7(a) and 3-7(b). These soundings are presented because of small temporal and spatial differences between the flight and the meteorological observations.

The temperature profile at Jacksonville at 1200 GMT (less than 3 hours prior to the report of no turbulence) is extremely smooth and regular with a gradual transition in the region of the tropopause from a negative lapse rate in the troposphere ( $-0.06^\circ\text{C}$  per 100 ft) to a positive lapse rate in the stratosphere ( $0.14^\circ\text{C}$  per 100 ft). The wind speeds are very light in the vicinity of the level of smooth flight ( $10 \text{ ft sec}^{-1}$  at 100-mb,

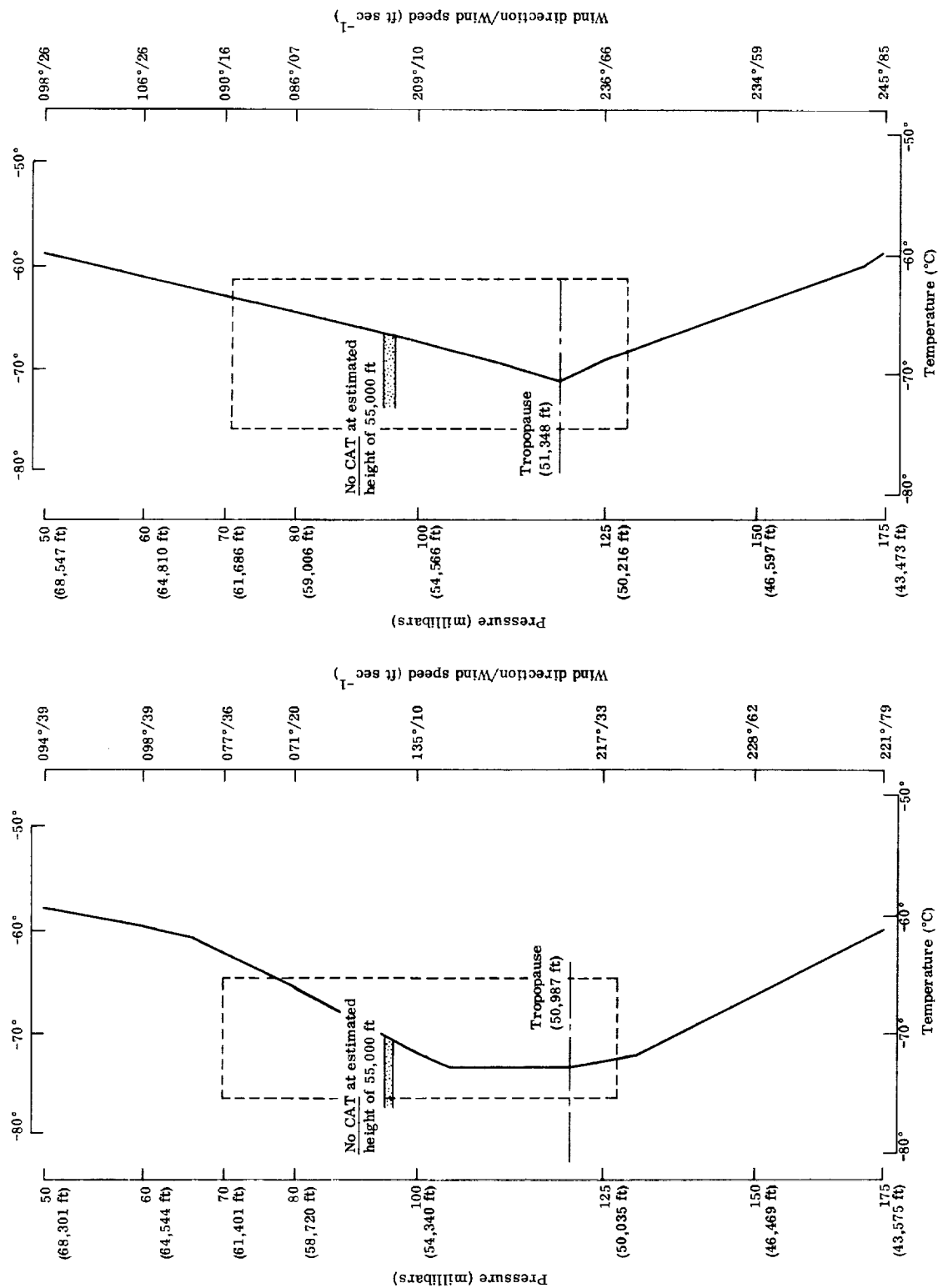


Fig. 3-7(a). Temperature and wind sounding at Jacksonville, Florida on September 11, 1967 (1200 GMT). The lack of turbulence was reported near the sounding location and 3 hours prior to the observation.

Fig. 3-7(b). Temperature and wind sounding at Charleston, South Carolina on September 11, 1967 (1200 GMT). The lack of turbulence was reported near the sounding location and 3 hours prior to the observation.

and  $20 \text{ ft sec}^{-1}$  at 80-mb) rendering the significant directional shear of  $64^\circ$  between these surfaces ineffectual for producing CAT. The vertical vector wind shear is only  $0.41 \text{ ft sec}^{-1}$  per 100 ft.

The sounding at Charleston was taken about three hours prior to the arrival of the U-2 aircraft in the area. The temperature sounding is very smooth with a complete absence of any inversion layers or other irregularities. Wind speeds closest to flight level are almost negligible ( $10 \text{ ft sec}^{-1}$  at 100-mb and  $7 \text{ ft sec}^{-1}$  at 80-mb) and consequently little significance can be attached to the large difference in wind direction between the two levels. The vertical vector wind shear at flight level is  $0.33 \text{ ft sec}^{-1}$  per 100 ft.

To summarize, a complete absence of any CAT on both north and south-bound segments of a flight along the Atlantic Coast occurred with the following conditions:

- Smooth vertical temperature profiles completely free of inversions or irregularities;
- Light wind speeds near flight level and small values of vertical vector wind shear;
- Weak horizontal temperature gradients at 100-mb (53,000 ft);
- Banded frontal (largely middle-tropospheric) clouds just to the east of flight.

November 28—December 2, 1967 (Severe Turbulence)

In the second quarterly progress report [ 27 ] an analyses was made of cloud characteristics and circulation features on November 30, 1967 for HICAT flight test No. 264. The sounding at Yucca, Nevada on December 1 (0000 GMT) is associated with moderate CAT. The flight track was located above a region of maximum wind speeds which exceeded  $197 \text{ ft sec}^{-1}$  at 200-mb. A trough at 100-mb, to the west of  $120^\circ\text{W}$  longitude, produced strong southwesterly flow. The satellite picture (opposite page) shows cirrus bands and evidence of transverse wave clouds over extreme southern Nevada where moderate CAT was encountered. A cirrus band is also seen over southeastern Utah to the south of the region where severe CAT was measured. Rather than expand upon this discussion, we will concentrate on the presentation of illustrations for several of the cases of intense CAT encountered during this period. During the

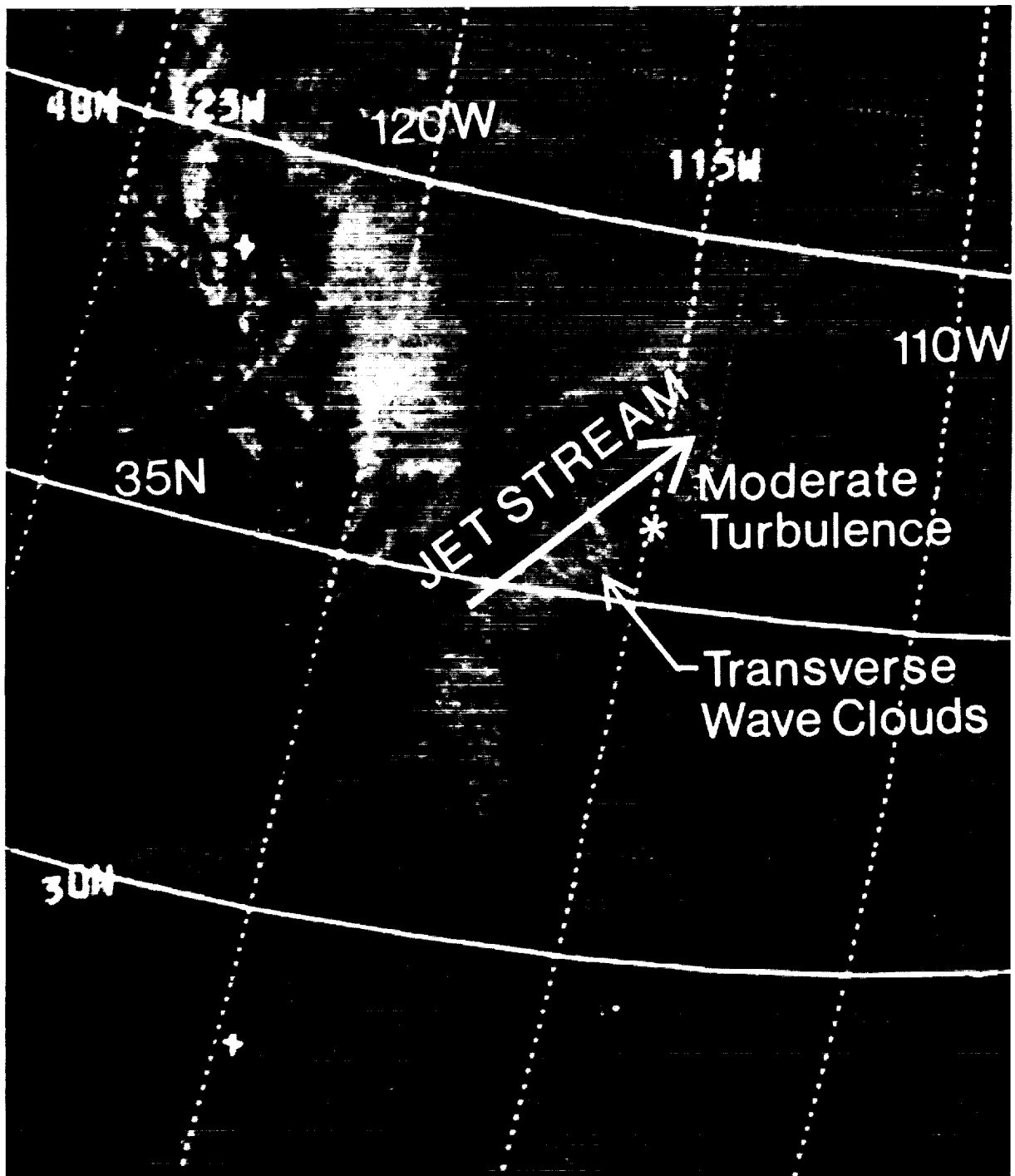


Plate 1. ESSA 3 satellite picture over southwestern United States on November 30, 1967 at 2038 GMT. Moderate CAT was encountered at 36°N, 115°W above a band of cirrostratus clouds associated with the jet stream. Wave activity is indicated by transverse clouds oriented perpendicular to the jet stream.

period November 28 through December 2 a total of 19 cases were defined as follows: severe, 3; moderate to severe, 1; moderate, 2; light, 7; very light, 3; and none, 3. The fact that only 3 of 19 cases were defined as completely free of turbulence is an indication of the abundance of CAT encountered during five research flights in the western United States.

Because of the infrequency of observing CAT as intense as moderate to severe or severe in either the Phase 2 or Phase 3 data samples it is most fruitful to discuss these four cases in some detail.

In the first case, the pertinent data is given in Fig. 3-8(a). Moderate to severe CAT was observed over Albuquerque, New Mexico on November 29, 1930 GMT, in the 56,100-ft to 60,400-ft layer. The upper boundary of this layer was 1,840 ft below an upper tropopause surface which defined the lower limit of a strong temperature inversion computed as  $0.61^{\circ}\text{C}$  per 100 ft. The negative lapse rate below the tropopause is  $-0.15^{\circ}\text{C}$  per 100 ft. The vertical vector wind shear both at and below the turbulence layer is rather large with computed values of  $1.3 \text{ ft sec}^{-1}$  per 100 ft in both instances and with a resultant Richardson Number of 1.4.

The second case, where severe CAT occurred between 59,700 ft and 63,000 ft on November 30 (2300 GMT) near Grand Junction, Colorado contained a problem with regard to meteorological data. The sounding at Grand Junction was missing which made it necessary to use data obtained at Denver, Colorado, about 135 miles to the east. In spite of the large distance of separation between the CAT and meteorological data the association of this case of severe CAT with the temperature profile shown in Fig. 3-8(b) is excellent. The lower limit of the severe CAT is marked by an extreme inversion of  $1.01^{\circ}\text{C}$  per 100 ft while the negative lapse rate below this inversion was computed as  $-0.21^{\circ}\text{C}$  per 100 ft. A second temperature inversion is present just above the CAT layer. The vertical wind shear is undoubtedly large in the thin lower temperature inversion layer but the values computed from the standard level wind data were rather small. This fact again points to the inadequacy of the standard radiosonde data for computing vertical wind shear in those instances when pronounced vertical wind shear is confined to layers of a few hundred feet thickness.

The third case of intense CAT was observed within a layer between 53,100 ft and 60,700 ft over Grand Junction at 0700 GMT on December 1. The associated

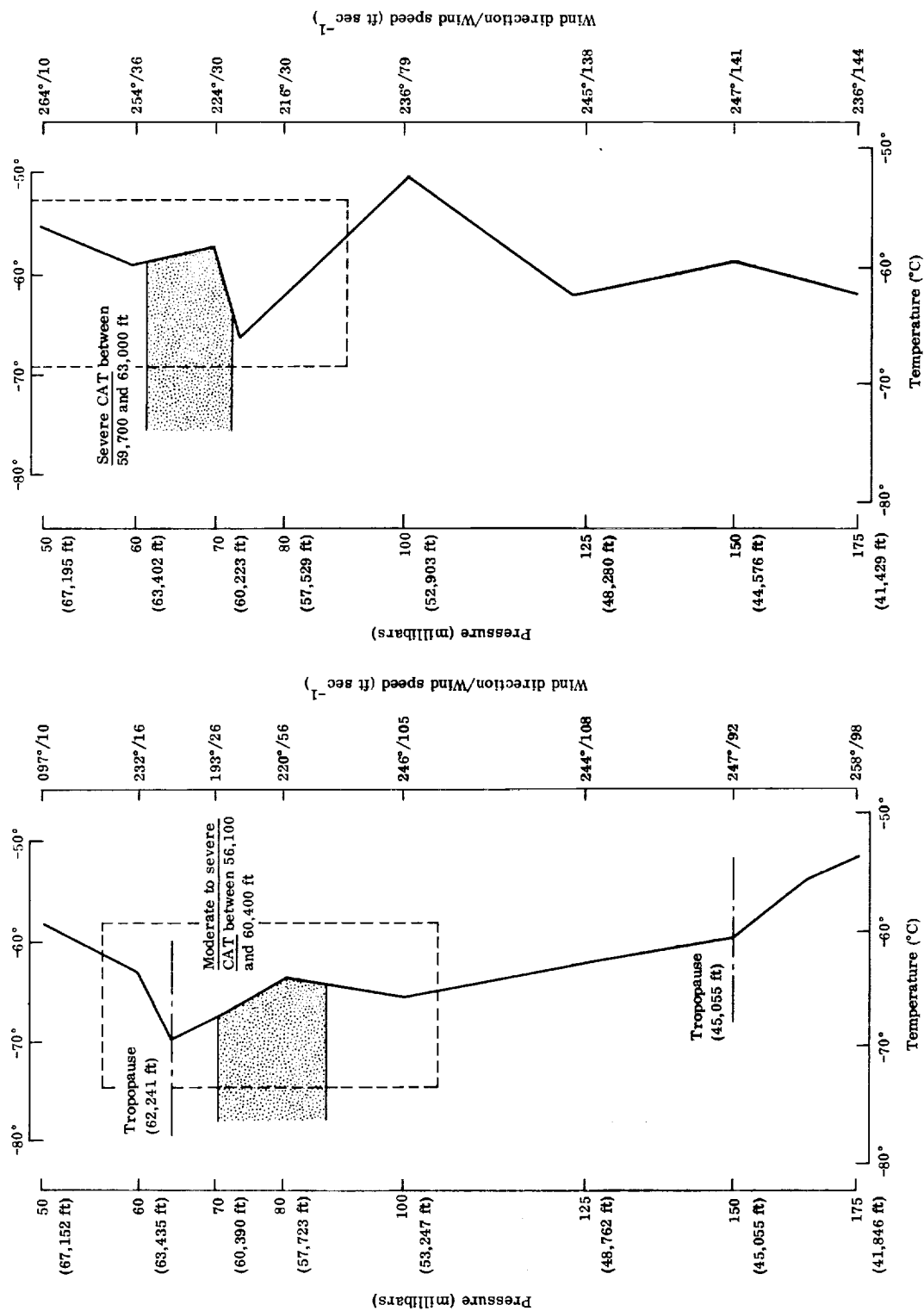


Fig. 3-8(a). Temperature and wind sounding at Albuquerque, New Mexico on November 30, 1967 (0000 GMT). The moderate to severe turbulence was reported near the sounding location and was encountered 4 hours prior to the observation.

Fig. 3-8(b). Temperature and wind sounding at Denver, Colorado on December 1, 1967 (0000 GMT). The severe turbulence was reported about 135 miles from the sounding location and was encountered 1 hour prior to the observation.

temperature profile shown in Fig. 3-9(a) is quite irregular and in particular exhibits a clearly defined double-inversion structure within the CAT layer. The lower inversion is computed as  $0.24^{\circ}\text{C}$  per 100 ft and the intervening thin layer between the two inversions has a rate of decrease of  $-0.27^{\circ}\text{C}$  per 100 ft. The vertical vector wind shear between the 80 and 70-mb constant pressure surfaces is  $1.6 \text{ ft sec}^{-1}$  per 100 ft resulting in a Richardson Number of 3.2.

The fourth case of intense CAT, again severe, was encountered in portions of the layer between 53,150 ft and 56,400 ft over Albuquerque, New Mexico at 2330 GMT on December 1. The temperature profile shown in Fig. 3-9(b) is an excellent illustration of the frequent double-inversion structure associated with more intense CAT. The upper inversion has an extremely large positive lapse of  $1.7^{\circ}\text{C}$  per 100 ft and the vertical vector wind shear is  $1.0 \text{ ft sec}^{-1}$  per 100 ft with an associated Richardson Number of 2.8.

An irregular lapse rate including both strong inversion layers and layers in which the temperature decreases rapidly with height was associated with each of four cases of intense CAT. A double inversion vertical temperature structure is clearly present in the final two cases and partially exhibited in the first two cases. Moderate or strong vertical vector wind shears were computed for three of the four cases

#### Summary of Meteorological Relationships

The analysis of the radiosonde data and Phase 3 CAT reports using both the statistical and case study approach has provided further strong evidence of the association of CAT with an irregular vertical temperature structure frequently containing a double inversion structure separated by an intervening layer in which temperature rapidly decreases with height. The numerical values computed for the temperature variables quantitatively describing these features are quite similar for both data samples. This result contains two important implications for the development of CAT detection instrumentation. First, the consistent numerical results imply that a vertical-scanning CAT detection sensor could be calibrated numerically to provide probabilistic estimations of encountering CAT of various intensity levels. Second, it would seem wise that the design and development of any airborne detection instrumentation should include the capability of vertical scanning as well as horizontal probing of the temperature field.



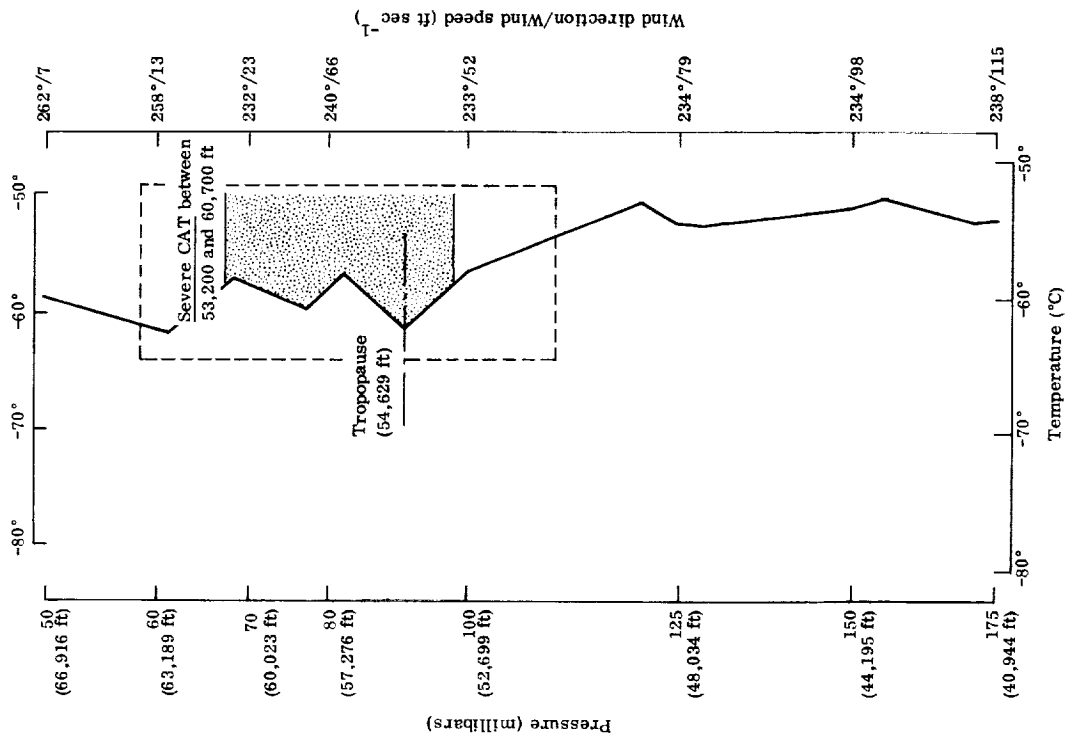


Fig. 3-9(a). Temperature and wind sounding at Grand Junction, Colorado on December 1, 1967 (1200 GMT). The severe turbulence was reported near the location and was encountered 5 hours prior to the observation.

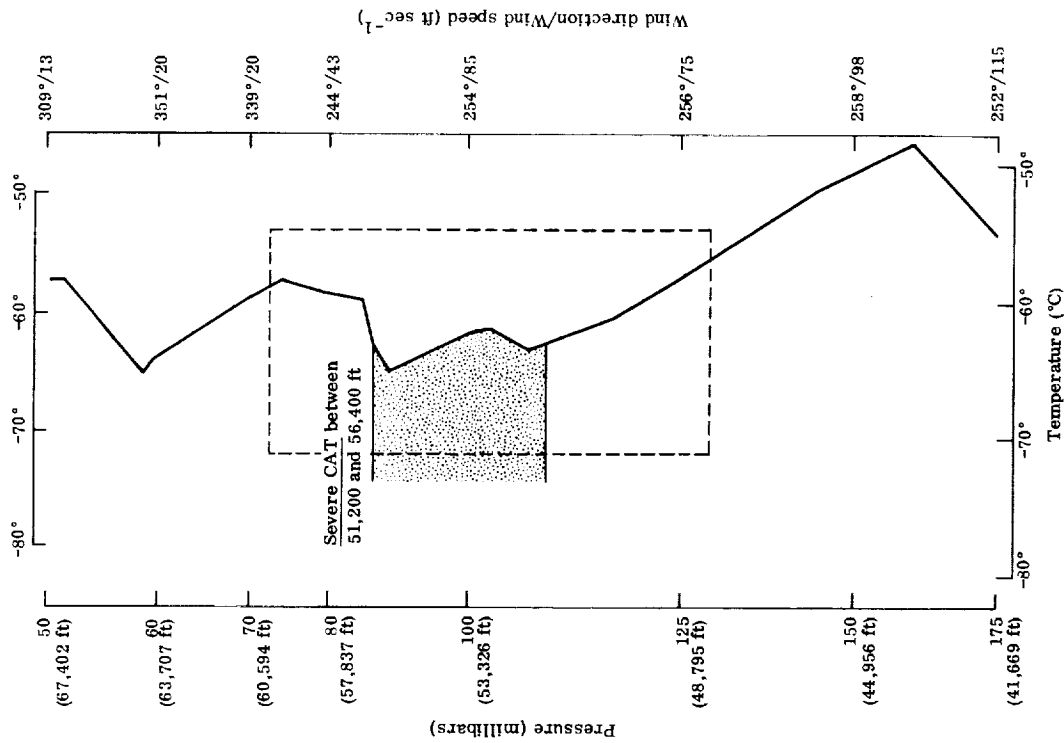


Fig. 3-9(b). Temperature and wind sounding at Albuquerque, New Mexico on December 2, 1967 (0000 GMT). The severe turbulence was reported near the sounding location and was encountered 1 hour prior to the observation.

Large differences between the maximum and minimum lapse rates within  $\pm 6500$  ft of the level of interest are indicative of an irregular rate and of significant clear air turbulence.

Large negative values of the minimum observed lapse rate (layer of rapidly decreasing temperature with altitude) and large positive values of the maximum observed rate (a strong inversion) are both related to significant CAT. Besides being indicative of an irregular lapse rate a strong temperature inversion is associated with locally large vertical wind shears while a layer of rapidly decreasing temperature-with-height is a region of decreased stability in a normally near-isothermal or stable stratosphere.

Large values of vertical vector wind shear centered on the level of interest and a large vertical gradient of kinetic energy are indicative of an increased likelihood of significant CAT. However, significant CAT may also occur when the wind speed is light and the large-scale vertical wind shear as computed from standard rawinsonde data is small. Large values of vertical wind shear are undoubtedly present in thin layers of several hundred feet thickness in association with observed temperature inversions. The vertical wind shears computed from the wind data however, represent layer thicknesses of several thousand feet and the computed larger-scale shears do not always indicate the presence of large values of wind shear in thin layers. More detailed resolution in the wind data (such as that obtained with the FPS-16 radar/spherical balloon) is required for greater utility. The vertical wind shear computed from standard data are likely to be most useful during the winter in well defined wind flows; however, if wind speeds are very high in the upper troposphere wind data may be missing in the stratosphere.

The joint consideration of the difference between the maximum and minimum lapse rates ( $\gamma_{\max} - \gamma_{\min}$ ) and the minimum Richardson Number ( $R'_{\min}$ ) most clearly isolate the probable occurrence of light to moderate or more intense CAT in the stratosphere. The minimum Richardson Number is computed from the minimum lapse rate and the appropriate vertical vector wind shear. Very consistent and satisfactory results were obtained with both the Phase 2 and Phase 3 samples from a joint consideration of  $\gamma_{\max}$  and  $\gamma_{\min}$ .

## B. Satellite Video Data

Cloud features and characteristics observed from weather satellite television pictures have been effectively utilized to deduce both macro- and meso-scale circulation features at levels throughout the troposphere and lower stratosphere. Many of these features can be used either directly or indirectly to infer probable regions of CAT occurrence and non-occurrence. An idealized model of pertinent cloud characteristics that can be derived from satellite video data was presented in our interim report [19] and is shown in Fig. 3-10. Many authors, particularly Whitney, et al. [28], Crooks, et al. [10] and Vizee, et al. [17] have conducted studies contributing to the summarized information.

The fourteen categories of cloud characteristics used in this study are listed below with some explanatory comments. Cloud type abbreviations used are:

St - Stratus	Cs - Cirrostratus
Sc - Stratocumulus	Cu - Cumulus
Ac - Altocumulus	Ci - Cirrus
As - Altostratus	Cb - Cumulonimbus

1. None to scattered clouds. These conditions are frequently characteristic of large areas of anticyclonic systems at the surface, ahead of an upper-level ridge or behind an upper-level trough [descending atmospheric motion (subsidence) and upper-level flow with a northerly component].

2. Broken to overcast St, Sc, Ac/As, Cs. These clouds may be indicative of a variety of atmospheric processes including some of relatively local origin (terrain induced) but clouds in this category do not exhibit the characteristics of the categories listed below.

3. Convective Cu-form and Ci >2° away. Convective activity is occurring in the general area but is well removed from the location of the aircraft CAT report.

4. Edge of Cb and Ci. The CAT observation is at the edge of thunderstorm occurrences and associated cirrus shield.

5. Over frontal cloud mass or band. This category describes elongated bands (may be 500-1000 miles or more) or masses of bright thick-appearing clouds associated with cold or occluded fronts usually having a horizontal width of several hundred miles.

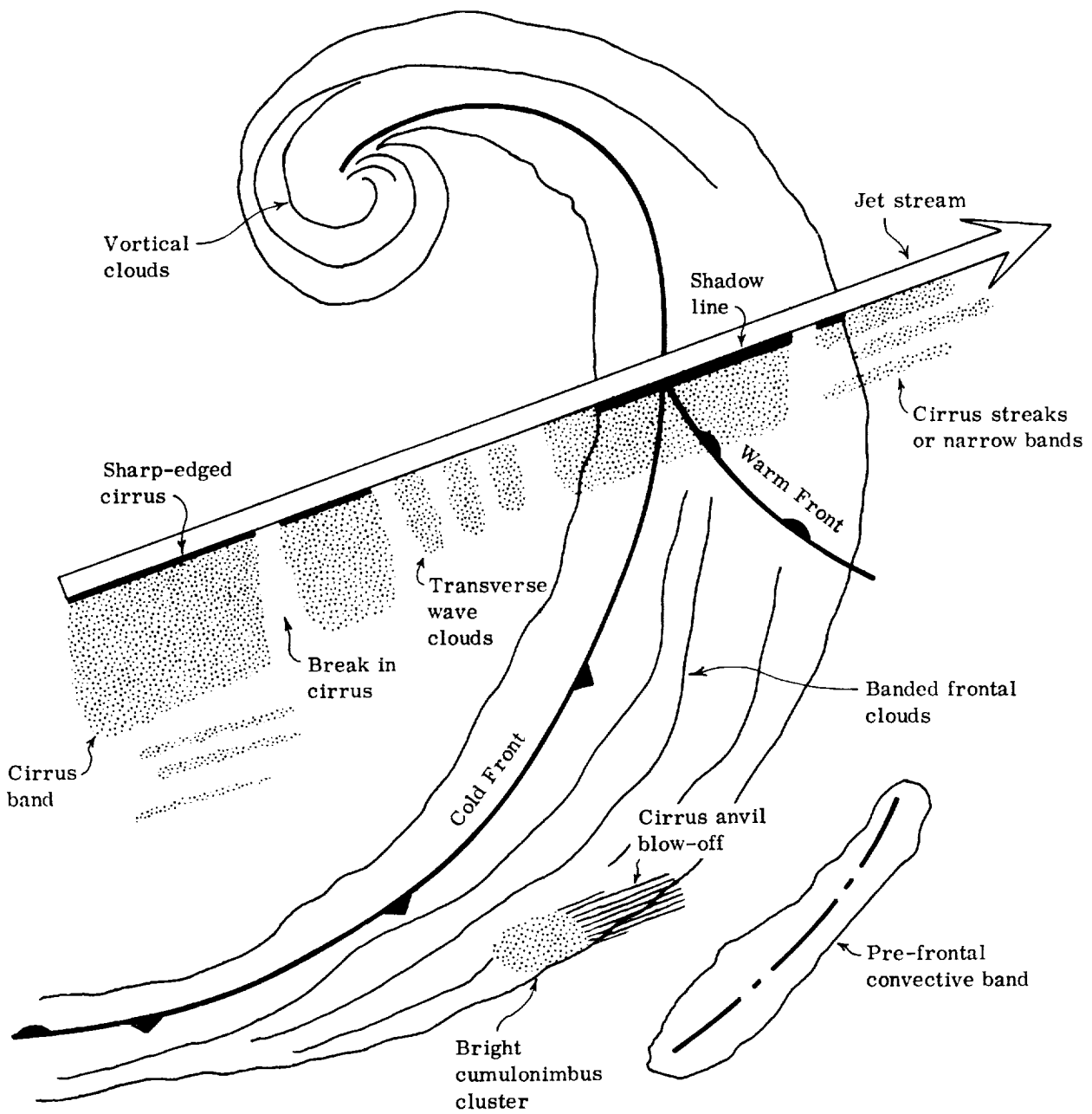


Fig. 3-10. Idealized characteristics of satellite video data.

6. Edge of broad frontal cloud mass.
7. Edge of frontal cloud band. The width of the cloud band is generally smaller and the cloud band is more "tightly" organized than in types 5 and 6.
8. Edge of vortex. Vortical clouds are associated with a surface cyclone.
9. Broken patches of Cu, Ac, Ci with Cs. The clouds are less well organized and do not exhibit the banded structure found in category 10, but association with the jet-stream is possible for Ci and Cs cloud types. The patchy nature of the clouds indicates regions of organized alternating upward and downward vertical motions facilitating vertical overturning and turbulent exchange.
10. Straight or curved Ac, Ci, Cs bands and streaks  $<2^\circ$  away. Elongated bands of Ci and Cs frequently are found in the 25,000-45,000 ft-layer above the surface on the southern side (to the right, looking downstream) of the jet stream. The northern edge of the cirrus when well-defined is close to the jet-stream core, a region of maximum wind speeds and large vertical wind shears. Streaks of Ci and Cs are also associated with jet-stream activity.
11. Convective Cu-form cells and bands  $<2^\circ$  away. Includes both isolated cells and lines of convective activity although Cb is not necessarily clearly present.
12. Transverse wave clouds. These clouds are nearly perpendicular to the direction of upper-level flow. The alternating cloudy and clear regions correspond to the upward and downward motions in a wave which is often terrain-induced. This cloud, at cirrus levels, indicates a potentiality of upward propagations of disturbances well into the stratosphere.
13. Over major vortex. This category includes vortical clouds associated with a major cyclone.
14. Over Cb. A bright Cb cluster is composed of several Cb clouds and in cases of strong thunderstorm activity the tops may extend to 50,000 ft or higher. Turbulence may be found in clear air well removed, either horizontally or vertically, from the Cb cloud. These clouds may occur in unstable air masses and in pre-frontal convective bands as well as in frontal systems.

The distance from a visible cloud feature is important with regard to the likelihood of CAT occurrence and the strength of the turbulence. Cloud features were

examined within 5° latitude or longitude of the CAT observation for selection of the major cloud feature. For this reason, the most severe CAT occurrence on a given day was first selected and then other CAT cases were considered only if they were more than 5° distant from each other. Thus, the procedures for defining occurrences and non-occurrences of CAT for association with satellite data differ somewhat from those described with the radiosonde and circulation data.

The comparison of the major cloud features from satellite pictures (ESSA-2, 3, 5) with two exhaustive categories of Phases 2 and 3 HICAT observations is given in Table 3-7. Considering the Phase 2 sample, a chi square value of 28.3 was obtained, and the probability that the categories are unrelated is only one percent. With respect to the individual lines of the table the five percent probability level for chi square with one degree of freedom is 3.841. The only calculated chi squares which exceed this are for cloud categories 1, 7, and 10. Thus, "none to scattered clouds" is significantly related in this sample to the occurrence of "none to light" turbulence in the stratosphere. The "edge of a frontal cloud band" is significantly related to light to moderate or greater turbulence. The occurrence of at least light to moderate stratospheric turbulence within 2° latitude or longitude of bands of cumulus or altocumulus with cirrus bands also appears to be significant. This significance is assumed from the chi square test indicating unlikely random occurrences of the frequencies in these three categories. For other individual cloud categories there were too few cases to enable definition of relationships.

Considering the Phase 3 sample, it is worth noting that the data contains a higher percentage of flights during times when significant convective activity occurred. The high frequency of light to moderate or more intense turbulence during these situations is seen from categories 4, 11, and 14 of the table. It should be kept in mind, however, that the turbulence particularly in categories 4 and 11 but also in category 14 may not be directly associated with the convective motions of the Cb cells. Rather, a more complex mechanism may be operative at the higher levels of the stratosphere involving upward perturbation of gravity waves induced by flow over the Cb mass with distortion in local zones of large vertical wind shear producing turbulence. The layers of large vertical shear should be marked by the presence of temperature inversions and an irregular vertical temperature profile.

TABLE3-7  
VIDEO FEATURES SUMMARIZED BY CLOUD CATEGORY

(a) Phase 2 HICAT Observations

Major cloud features	Number of CAT cases	
	None through light	Light to moderate or greater
1. None to scattered clouds	22	1
2. Broken to overcast St, Sc, Ac/As, Cs	8	0
3. Convective Cu-form and Ci > 2° away	6	0
4. Edge of Cb and Ci	4	0
5. Over frontal cloud mass or band	3	0
6. Edge of broad frontal cloud mass	7	0
7. Edge of frontal cloud band	1	3
8. Edge of vortex	7	2
9. Broken patches of Cu, Ac, Ci with Cs	3	2
10. Straight or curved Ac, Ci, Cs bands and streaks ≤ 2° away	6	5
11. Convective Cu-form cells, and bands ≤ 2° away	2	2
12. Transverse wave clouds	0	1
13. Over major vortices	1	1
14. Over Cb	1	2
Totals	71	19

(b) Phase 3 HICAT Observations

1. None to scattered clouds	26	5
2. Broken to overcast St, Sc, Ac/As, Cs	5	1
3. Convective Cu-form and Ci > 2° away	2	0
4. Edge of Cb and Ci	2	3
5. Over frontal cloud mass or band	10	1
6. Edge of broad frontal cloud mass	5	2
7. Edge of frontal cloud band	1	1
8. Edge of vortex	2	0
9. Broken patches of Cu, Ac, Ci with Cs	5	2
10. Straight or curved Ac, Ci, Cs bands and streaks ≤ 2° away	12	8
11. Convective Cu-form cells and bands ≤ 2° away	4	5
12. Transverse wave clouds	0	2
13. Over major vortex	1	0
14. Over Cb	1	6
Totals	76	36

The association of CAT in the stratosphere with regions of strong wind flow at the tropopause discontinuity (jet stream) and potential wave activity is shown by categories 10 and 12. Finally, categories 1, 2, and 5 are most clearly associated with a high frequency of encountering no turbulence or only light CAT. Categories 1 and 2 essentially denote an absence of any clouds or any significant cloud feature related to circulation systems that might be productive of CAT. Category 5 implies that the presence of a front in the mid-troposphere is per se, not an indication that CAT might be expected in the stratosphere. One must look for more dramatic indications of energy exchange at higher levels in the vertical (jet stream presence, transverse wave occurrence, cumulonimbus clouds) to expect to encounter evidence of an irregular dissipation of kinetic energy (CAT).

The chi square value obtained for the overall Phase 3 table was 28.7, significant at the one percent level. Of all categories, 12 and 14 were significant at the five percent level and category 1 was nearly significant (chi square computed as 3.7).

#### Video Features Summarized by Cloud Categories

For most of the 14 cloud characteristic categories given in Table 3-7 similar results were obtained for both Phase 2 and Phase 3 samples. The main comparisons and conclusions are listed below.

1. No clouds or cloudiness without distinguishable characteristics (categories 1 and 2) was associated with smooth flight or only light turbulence in both samples.
2. Convective and cumulonimbus clouds (categories 4, 11 and 14) were observed more often in the Phase 3 period and the association with significant (light to moderate and more intense) turbulence was more evident. In the Phase 3 sample in these 3 categories, 14 of 21 cases were associated with significant CAT while the proportion was 4 of 11 from the Phase 2 sample.
3. The presence of a broad frontal cloud mass (categories 5 and 6) was not an indicator of significant CAT in either sample period.
4. Cirrus and cirrostratus bands and streaks (often associated with the jet stream) and broken patches of altocumulus and cirrus (categories 9 and 10) are associated with a greater proportion of significant CAT than the overall sample frequency of CAT. The proportion of cases of significant CAT in these two cloud categories is 7 of 16 in the Phase 2 period and 10 of 27 in the Phase 3 period.



As a final step in evaluating the association of cloud characteristics with CAT the results from Phases 2 and 3 were combined. An overall chi square of 53.4 reflects the greater statistical reliability with 202 cases. The 14 x 2 table was then compressed to a 3 x 2 table by combining the cloud feature categories as shown in Table 3-8.

Thus, when the cloud features in Group 1 of Table 3-8 are seen on a satellite photograph the probability of encountering significant CAT (light to moderate and more intense) anywhere in the vicinity of the features is very low. The probability of encountering significant CAT within 2° of the cloud features in Group 2 is perceptibly higher, but only in Group 3 does the appearance of the associated cloud features indicate that significant CAT is probable.

TABLE 3-8  
COMBINED SATELLITE CLOUD CATEGORIES RELATED TO  
PHASES 2 AND 3 HICAT DATA

Group	Cloud Feature Categories	Number of CAT cases		Total
		None-light ( $<  \pm 0.25g $ )	Light to moderate or greater ( $>  \pm 0.25g $ )	
1	1 - None to scattered clouds	103	12	115
	2 - Broken to overcast stratus, strato-cumulus, altocumulus, altostratus			
	3 - Convective Cu-form and cirrus $> 2^\circ$ away			
	5 - Over frontal cloud mass or band			
	6 - Edge of broad frontal cloud mass			
	8 - Edge of vortex			
2	4 - Edge of cumulonimbus and cirrus	16	8	24
	9 - Broken patches of altocumulus and cirrus			
	13 - Over major vortex			
3	7 - Edge of well-defined frontal band	28	35	63
	10 - Straight or curved cirrus, cirro-stratus or altocumulus bands and streaks $< 2^\circ$ away			
	11 - Convective Cu-form cells and bands $< 2^\circ$ away			
	12 - Transverse wave clouds			
	14 - Over cumulonimbus			
Total		147	55	202

### C. Atmospheric Circulation Features

A tabulation of circulation features was performed for all cases involving occurrence and non-occurrence of CAT in the stratosphere as defined from the HICAT sample—Phases 2 and 3. The objective was to determine the extent of synoptic association existing between CAT in the stratosphere and principal circulation features at the surface, 300 mb and 100 mb. The analyses used in most cases were those published for 24-hour intervals by the Free University of Berlin [23, 24, 25, 26]. For some cases, six-hourly surface charts from the National Meteorological Center were available. An attempt was made to allow for temporal changes in circulation features. Since the difference in time between the turbulence occurrence or non-occurrence and the meteorological analysis may be up to 12 hours and was on the average about 6 hours, a sophisticated scheme for associating the CAT with circulation features was clearly not warranted.

The circulation features and categories examined are given below:

#### Surface Analysis

(a) Presence of frontal boundary at the surface within 5° longitude of location of occurrence or non-occurrence:

(b) Presence of cyclone center within 10° longitude of location.

#### 300 mb Analysis

(a) Contour Curvature—Cyclonic; Anticyclonic; or Straight.

(b) Position relative to trough and ridge lines:

- within ~ 5° longitude of trough line; ahead of trough;
- within ~ 5° longitude of ridge line; behind ridge;
- within ~ 5° longitude of ridge line; ahead of ridge;
- within ~ 5° longitude of trough line; behind trough;
- none of the above.

(c) Within 10° longitude of closed low (closed contour).

### 100 mb Analysis

Note that the 100 mb surface is normally located near 53,000 ft while the 50 mb surface is usually located at about 68,000 ft. Thus, for most flights, the 100 mb surface is closer to the level of occurrence and is, in general, to be considered the level of greater interest for all occurrences under 62,000 ft. The 70-mb constant pressure surface analyses were not available.

- (a) Contour curvature—cyclonic; anticyclonic; straight.
- (b) Position relative to trough and ridge lines:
  - within  $\sim 5^\circ$  longitude of trough line; ahead of trough;
  - within  $\sim 5^\circ$  longitude of ridge line; behind ridge;
  - within  $\sim 5^\circ$  longitude of ridge line; ahead of ridge;
  - within  $\sim 5^\circ$  longitude of trough line; behind trough;
  - none of the above.
- (c) Characteristic of Isotherm Field (smoothed):
  - Generally parallel to height contours;
  - Wave-like or generally cross ( $\geq 30^\circ$ ) contour flow (advection);
- (d) Temperature gradient (smoothed):
  - $<4^\circ \text{C}/5^\circ$  longitude (weak);
  - $4$  to  $8^\circ \text{C}/5^\circ$  longitude (moderate);
  - $\geq 8^\circ \text{C}/5^\circ$  longitude (strong).

A certain degree of subjectivity was present in the tabulation of circulation features. This is acceptable considering the smoothed nature of the original analyses and the temporal differences between meteorological and turbulence data. Thus, the results obtained provide only broad guidance.

The relationships between circulation features and categories of CAT intensity demonstrated by the analysis were modest at best. This is not too surprising considering the broad, general nature of the circulation categories and the moderate sample size. While, as was demonstrated in Section 3A, the sample size is adequate to develop well-defined relationships between CAT intensity and selected meteorological variables, the generalized nature of the circulation features probably requires a more substantial sample.

The combined results for Phases 2 and 3 are given in Table 3-9. For each circulation feature the distribution in terms of percentage is shown for three turbulence categories: none to very light; light; and light to moderate or more intense. The total number of cases is given for each turbulence category and the overall frequencies are given at the bottom of both tables. The five cases defined from flights based in Panama (Phase 3 data) were not included because circulation features are difficult to determine at very low latitudes.

Considering all cases, the variations that seem most consistent are:

- A surface front is present 69% of the time when light to moderate or more intense CAT is occurring and only 56% of the time when no turbulence or very light CAT is encountered.
- Light to moderate or more intense CAT rarely occurred behind the 100-mb trough (6% of cases) or ahead of the 100-mb ridge (6% of cases). Since these essentially represent the same region of the circulation the statistics reinforce each other.
- Probably of greatest significance are strong 100-mb temperature gradients which occur 17% of the time when light to moderate or more intense CAT is encountered and only 8% of the time when no turbulence or very light CAT is present. The temperature gradient was classified as weak 45% of the time with no turbulence, and only 21% of the time with light to moderate or more intense CAT.

The principal difference between results obtained from the Phase 2 and Phase 3 samples is with regard to the characteristics of the isotherm fields at the 100-mb constant pressure surface. In the Phase 2 sample, there was a tendency for light to moderate or more intense CAT to be more likely when the isotherm field was cross-contour (cold or warm advection occurring) [19]. This is not true with the Phase 3 sample, in fact, there is a slight tendency for the reverse relationship. An explanation for this inconsistency is proposed from a review of individual cases in the Phase 3 sample. Frequently, with none or very light CAT, weak temperature gradients were evident (40% of the time). Often, the analyzed isotherms were "wandering" across contours and sometimes had a wave shape. Actually, little advection was occurring because the temperature gradient was weak. Under conditions of moderate or strong temperature gradients at 100 mb the isotherm field was more often in phase with the

**TABLE 3-9**  
**PERCENT FREQUENCY DISTRIBUTIONS OF CIRCULATION FEATURES STRATIFIED**  
**ACCORDING TO CAT INTENSITY - PHASES 2 AND 3 DATA**

CAT Intensity		Surface				300 mb										Total cases
		Front		Cyclone		Curvature			Trough-Ridge					Closed low		
									Behind trough	Ahead of trough	Behind ridge	Ahead of ridge	None			
Peak Acceleration Increment (g)	Description	Yes	No	Yes	No	Cyclonic	Anti-cyclonic	Straight	Behind trough	Ahead of trough	Behind ridge	Ahead of ridge	None	Yes	No	
<   ±.10   ±.10-±.25 >   ±.25	None and very light	56	44	38	62	52	35	13	18	29	10	19	24	27	73	
	Light	60	40	35	65	48	23	29	12	25	8	9	46	22	78	
	≥ Light to moderate	69	31	47	53	47	29	24	16	26	14	13	31	25	75	
Overall distribution		59	41	39	61	50	31	19	16	27	10	15	32	25	75	
		368														

CAT Intensity		100 mb													Total cases	
		Curvature			Trough-Ridge					Isotherm			Temperature gradient			
Peak Acceleration Increment (g)	Description	Cyclonic	Anti-cyclonic	Straight	Behind trough	Ahead of trough	Behind ridge	Ahead of ridge	None	Cross-contour	Wave shape	Parallel to contour	Weak	Mod.	Strong	
<   ±.10   ±.10-±.25 >   ±.25	None and very light Light ≥ Light to moderate	48	25	27	15	21	8	11	45	32	23	45	45	47	8	209
		49	26	25	11	21	8	7	53	32	16	52	29	61	10	86
		42	27	31	6	25	8	8	53	34	12	54	21	62	17	73
Overall distribution		47	26	27	12	22	8	9	49	33	20	47	37	53	10	368

contour pattern in the Phase 3 sample than was the case with the Phase 2 sample. At all times, in evaluating these results the smoothed large-scale characteristics of the analyses obtained must be recognized. Perhaps the most useful relationship of the 100-mb isotherm field with CAT would be obtained by considering the characteristics of the isotherm field (cross-contour and wave-shape) only when the temperature gradient is at least of moderate strength.

We may summarize the relationship between CAT and circulation features as follows:

- Light to moderate or more intense CAT is associated with an increased frequency of large horizontal temperature gradients at the 100 mb constant pressure surface. This result is in agreement with the findings of Ashburn, et al. [29].
- Concentrations of kinetic energy in the atmosphere as reflected in surface fronts were found to occur more frequently under regions of turbulence in the stratosphere than when stratospheric flow is smooth.
- Light to moderate CAT in the stratosphere was not clearly related to the contour curvature or the trough-ridge positions at the 300-mb surface. Significant CAT is infrequent in the region ahead of the 100-mb ridgeline and behind the trough.

#### 4. LOCATING REGIONS OF CLEAR AIR TURBULENCE

Modern turbulence theory views the problem of clear air turbulence in terms of a cascade of energy from long wavelength flow (general circulation) to very small-scale transient circulations. An aircraft, depending on its size, design and cruising speed, will of course be sensitive only to a particular wavelength interval. To predict the likelihood of an aircraft encountering turbulence, however, one must be aware of atmospheric conditions over a broader scale of motion. To generalize, one is concerned with locating regions of the atmosphere where significant potential or kinetic energy is present and there exists a mechanism (thermal instability or shearing of the flow) to convert or dissipate this energy toward a smaller scale in an abrupt manner and at a non-uniform rate resulting in fluctuations of the flow. With these background remarks let us consider the prediction procedure primarily from the following viewpoint: The satellite data and circulation features provide information on the general level of energy while the sounding data indicate the presence of a conversion mechanism.

In formulating a procedure for locating or predicting CAT in the stratosphere we must be cognizant of several considerations. The results of research performed in this study and elsewhere provide both general insights and specific relationships between CAT occurrence and environmental characteristics. The procedures developed are dependent on data availability and quality, and operational constraints in using the data. There are a variety of user requirements and we were particularly aware of the need to provide a basis for the development of design criteria for detection instrumentation.

A set of guidelines for locating regions of CAT should start with a realization of the climatological information available regarding CAT occurrence. The most relevant and recent climatological studies of CAT in the stratosphere have been compiled from analyses of HICAT data by Ashburn, et al. [29], Crooks, et al. [21] and Ashburn et al. [16]. Ashburn, et al. [29] determined the percentage of flight miles in turbulence over mountains (height of terrain greater than 3000 ft) to be 6.9%, while over flat lands (height less than 3000 ft) and large water masses the percentage was 5.5%. If only moderate or more intense CAT is included the percentages for mountains are 2.1%, for

flatlands 1.8%, and for water 1.0%. Crooks, et al. [21] in a somewhat different analysis compared for all HICAT tests the percentage of turbulence runs with the percentage of flight time in terrain categories of water, flat lands (relief difference less than 2500 ft) and mountains (relief difference greater than 2500 ft). The results are found below in Table 4-1.

**TABLE 4-1**  
**PERCENTAGE OF TURBULENCE**

Percentage	Water	Flat lands	Mountains
Percentage of flight time	27%	37%	36%
Percentage of turbulence runs	11%	41%	48%

Not only is CAT more frequently encountered over land than water but the likelihood of the turbulence being of moderate to severe intensity is greater.

Ashburn, et al. [16] also concluded that the intensity and frequency of occurrence of turbulence above 55,000 ft decreased with altitude over water and low relief terrain, but did not decrease with increasing altitude over mountains. Aircraft turbulence was observed nearly twice as frequently with a head wind as opposed to a tail wind. The examination of current data can, however, considerably alter these climatological expectancies.

The general procedure for locating regions of CAT in the stratosphere follows:

(1) From an examination of features contained in circulation analyses and satellite pictures one determines those regions where the occurrence of CAT is most likely (centers of energy) and also those regions where CAT occurrence is least probable. The circulation analysis at the pressure level closest to the flight level or layer of interest is, of course, to be particularly studied.

(2) Available radiosonde data are then examined in a sequence dictated by the analysis in step (1) both for the general profile of temperature and winds and to obtain quantitative measures of meteorological variables related to CAT occurrence. A specific objective, of course, is to focus on regions of smaller horizontal and vertical dimension where significant CAT is expected than is possible from an



analysis of circulation or satellite features. In regions where few or no radiosonde observations are available temperature information could be supplemented using data from the Satellite Infrared Spectrometer (SIRS) on the Nimbus satellite. The instrumentation was designed primarily for obtaining stratospheric and upper tropospheric temperatures.

Circulation Features to be particularly examined are:

(Indicators of increased likelihood of CAT occurrence)

- Presence of surface front and to a lesser extent surface cyclone;
- Large horizontal temperature gradient at 100-mb constant pressure surface (or constant pressure surface in stratosphere closest to layer of concern).

(Indicators of decreased likelihood of CAT occurrence)

- Region approximately 5° longitude ahead of ridgeline or behind trough line on the 100-mb constant pressure surface;
- Weak or non-existent horizontal temperature gradients at the 100-mb surface.

Satellite Features to be noted are:

(Indicators of increased likelihood of CAT occurrence)

- Within 140 mi of cirrus bands and streaks or cumuliform and altocumulus bands;
- At the edge of well-defined frontal cloud bands;
- Near transverse wave clouds;
- Over cumulonimbus.

(Indicators of decreased likelihood of CAT occurrence)

- Areas of nearly clear skies (no banded clouds);
- Areas of broken to overcast stratiform clouds;
- No cumuliform clouds indicating moderate to strong convection or cirrus bands within 140 miles.

The radiosonde data yielding vertical temperature and wind profiles can be studied subjectively and can be employed to compute numerical measures of meteorological variables using the computer program developed in this study. The variables may be computed relative to any specified level or series of levels.

Analyses of the sounding data clearly show significant CAT in the stratosphere to be associated with atmospheric conditions that tend toward greater thermal or kinetic instability and hence the presence of a mechanism to convert larger scale motions to smaller scale turbulent fluctuations. Specifically, light to moderate or more intense CAT is considerably more frequent when the temperature lapse about the level of interest is irregular and includes both strong inversions (locally large vertical wind shear) and layers in which the temperature rapidly decreases with height (a region of decreased thermal stability within a thermally stable stratosphere). These conditions were best reflected by numerical results associated with the five variables given below in Table 4-2. Also given with each variable are the category limits generally differentiating between the following categories: no turbulence and very light; and light to moderate or more intense CAT.

TABLE 4-2  
SUMMARY OF METEOROLOGICAL VARIABLES RELATED TO CAT

Variable*	Category Limits
$\gamma_{\max} - \gamma_{\min}$	(a) < 0.27 °C/100 ft (b) > 0.43 °C/100 ft
$\gamma_{\max}$	(a) < 0.15 °C/100 ft (b) > 0.25 °C/100 ft
$\gamma_{\min}$	(a) > -0.10 °C/100 ft (b) < -0.17 °C/100 ft
$R'_{\text{imi}}$	(a) > 15 (b) < 3.5
$\bar{V} \cdot \frac{\Delta \vec{V}}{\Delta Z}$	(a) < 23 $\frac{\text{ft}^2/\text{sec}^2}{100 \text{ ft}}$ (b) > 40 $\frac{\text{ft}^2/\text{sec}^2}{100 \text{ ft}}$

(a) no turbulence or very light CAT,  
(b) light to moderate or more intense  
CAT is likely.

\*Definition of variables—page 15.

The above five variables are the most significant results obtained from the analysis of CAT occurrence with respect to radiosonde data. Light to moderate or

more intense CAT occurs with the following conditions:

(1) The difference between the maximum and minimum lapse rates in the layer about the level of interest ( $\pm 6500$  ft) is large indicating an irregular lapse rate and rapidly changing stability in the vertical. Very large differences are frequently computed when the temperature profile exhibits a double-inversion structure, with the temperature inversions separated by a layer in which the temperature decreases with altitude.

(2) A large increase in temperature with altitude is often confined to a relatively thin inversion layer with locally large values of vertical vector wind shear. The vertical shear computed from the standard rawinsonde data may be rather small due to the absence of sufficient vertical resolution.

(3) A large decrease in temperature with altitude within a generally isothermal or relatively stable stratosphere indicates a region of lower stability.

(4) The Richardson Number computed with the minimum lapse rate will tend to be small when either the temperature decreases rapidly with altitude or the vertical wind shear is large.

(5) Large values of the vertical gradient of kinetic energy are most likely in the lowest layers of the stratosphere, just above the tropopause where strong wind speeds and vertical wind shear are most frequently encountered. The vertical vector wind shear may also be large in moderate flow when the wind direction changes rapidly with height.

The analysis of the Phase 2 and Phase 3 samples showed that the occurrence of CAT in the stratosphere was most consistently related to the temperature-derived variables and the minimum Richardson Number. The relationship of CAT to wind-derived variables was less satisfactory with considerable differences in results.

A final step in the procedure of delineating limited regions of probable significant CAT involves the use of the graphs given in Figs. 3-1 and 3-2. On these graphs, Sectors I, II and III defined with axes of  $R'_{\text{lim}}$  vs.  $(\gamma_{\text{max}} - \gamma_{\text{min}})$  and  $\gamma_{\text{min}}$  vs.  $\gamma_{\text{max}}$ . Only when the values of the variable combinations produced an intersection in Sector III was light to moderate or more intense CAT frequently encountered in both the Phase 2 and Phase 3 HICAT data samples.

## **5. RECOMMENDATIONS**

The objective of this study was to determine relationships between CAT in the stratosphere and parameters determined from radiosonde and rawinsonde data, circulation analyses and satellite pictures of cloud structure. The research was specifically directed toward identifying those categories and ranges of values of atmospheric parameters most clearly associated with significant (light to moderate or more intense) CAT for subsequent design of detection instrumentation. For this purpose, 372 cases of CAT occurrence and non-occurrence were defined from Phase 2 and Phase 3 HICAT aircraft measurement samples.

The relationships between significant CAT and numerical values of temperature-derived variables describing vertical profile characteristics were quite consistent in both the Phase 2 and Phase 3 samples. This result contains two important implications for the development of CAT detection instrumentation:

- The design and development of any airborne detection instrumentation system should include the capability of vertical scanning as well as horizontal probing of the temperature field. Kadlec [14] in his study of a limited sample of XB-70 test flights also concluded that vertical scanning capabilities were required.
- The consistent numerical results obtained with both Phase 2 and Phase 3 data imply that a vertical-scanning CAT detection sensor could be calibrated numerically to provide probabilistic estimations of encountering CAT of various intensity levels.

Through the years there has been a gradual increase in our knowledge of CAT occurrence and our understanding of the distribution of the temperature and wind field associated with turbulence. Current plans [2] and proposed programs [3] seek to build on the present level of knowledge by acquiring the more detailed and comprehensive data necessary for improved understanding of the CAT phenomenon and detection techniques.

Three areas in which further study is required are discussed below:

- There is a need for more adequate knowledge of the occurrence of CAT in the middle stratosphere above 65,000 ft. This includes knowledge of frequency, duration, dimensions, distribution (seasonal and geographical variations) and relationships to atmospheric variables and features. Specifically, YF-12 aircraft measurements of

turbulence should be related to meteorological data in preparation for the advent of SST flight.

- The relationship between horizontal and vertical temperature gradients associated with occurrences and non-occurrences of CAT provide important information for the development of CAT detection instrumentation. Scale is of particular concern here and there is a need to study the relationship of the mesoscale and microscale temperature fluctuations observed by an aircraft to the vertical temperature profile.

- The relationship between CAT occurrence in the stratosphere and the vertical temperature profile and stability variations in the vertical should be further investigated from two points of view. First, vertical temperature profiles derived from standard radiosonde observations, and special observations such as those obtained from the FPS-16 radar/spherical balloon and the Nimbus-SIRS data should be compared for relative utility in specifying the occurrence of CAT. Currently, frontal inversions and small-scale vertical features are not available from satellite data [30]. However, the Satellite Infrared Spectrometer data can presently provide valuable information on the location of the tropopause. Second, more effort should be directed toward developing a model or parameterization of the vertical temperature profile in association with CAT occurrence. This would include studying the relationship between CAT occurrence and the vertical variation of stability, the rate of change of temperature with height, and the degree of irregularity as evidenced by the frequency of sign reversal, magnitude of change and the rate of change of slope.

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